Neutrino Experiment

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CTEQ

11 July, 2015

- ν oscillations (T2K)
- ν oscillations $\rightarrow$ νA cross sections
- MINERvA - CC pion production results
- ν oscillations (sterile ν, MiniBooNE)
- Future

Neutrinos…

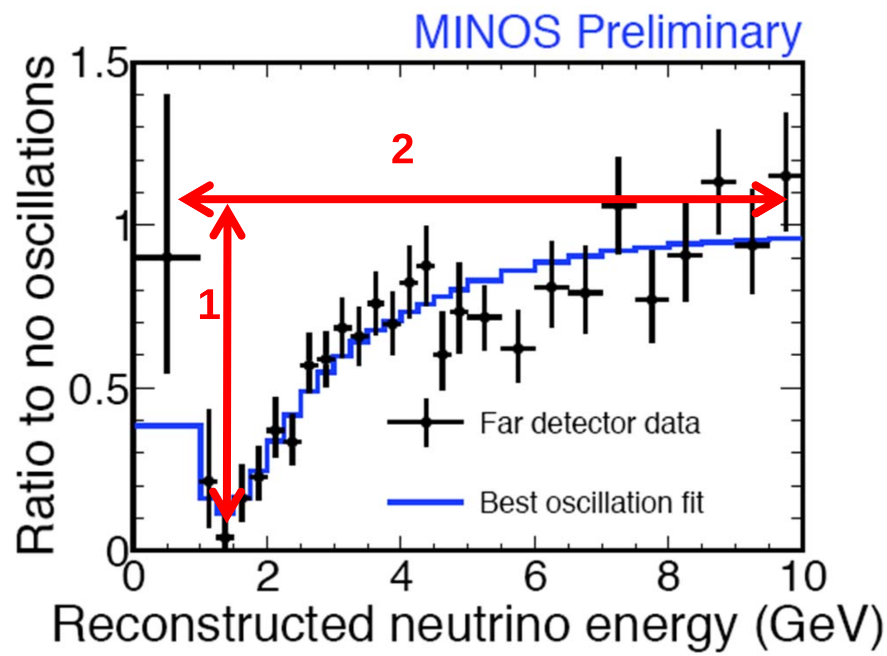
- ν are fundamental (sort of)
  - Mass from Higgs VEV coupling to right-handed ν? (hard to decide?)
  - Majorana or Dirac? ($0\nu\beta\beta$)
- ν are weird (definitely)
  - Long mean free path (ly) makes experiments very difficult (yrs)
  - Historically, many early ν experiments obtained Nobel Prize.
  - Closeness in mass of 3 known flavors makes oscillation easy to measure (different physics than K^0, B^0 - PMNS vs. CKM mixing)
  - CP violation in lepton sector source of matter-antimatter imbalance?
  - Lack of a limit on number of flavors (sterile) gives many possibilities
- US high energy physics has decided to go after lepton CP violation through ν oscillation as a primary goal (DUNE/FNAL). Cost will be >$1B!

ν Oscillation - disappearance

- Think of it as 2 coupled oscillators (normal vs. osc mode)
- E.g. ν_μ disappearance is standard measurement

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta}_{1} \sin^2(1.267 \underbrace{\Delta m^2}_{2} L/E)$$

- 1 mixing angle, 1 squared mass diff.
- Use wide-band beam
- Measure # of ν_μ in near (all ν_μ), far (oscillated sample) detectors.
- Take ratio as a function of E_ν
- Collect your prize!



ν Oscillation - appearance

- If neutrinos have mass, the flavor eigenstates are mixtures of the mass eigenstates. The neutrino mass matrix has 6 parameters.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

2 square mass differences (**Δm^2_{21}, Δm^2_{32}**),
3 mixing angles (**$\theta_{12}, \theta_{23}, \theta_{13}$**)
1 CP violation phase, **δ_{CP}**.

- **Δm^2_{21} and θ_{12}** were determined by solar/reactor neutrino oscillation.

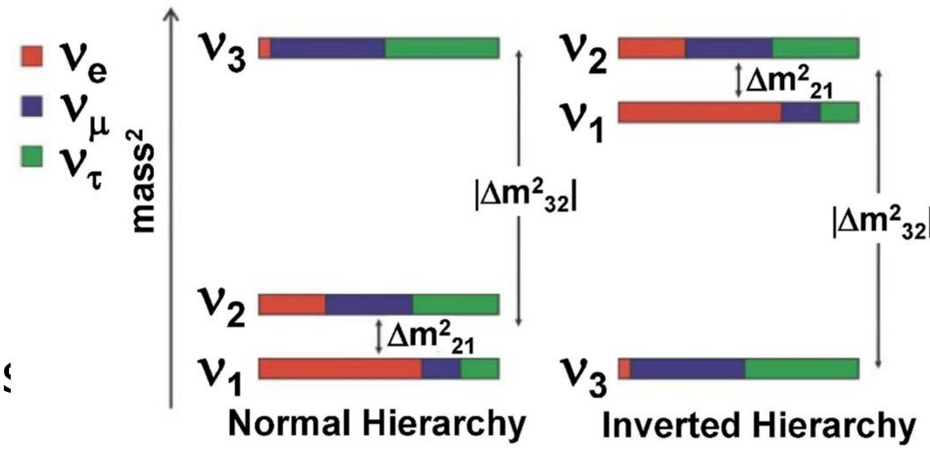
  $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2, $\sin^2 2\theta_{12} = 0.857 \pm 0.024$

- **$|\Delta m^2_{32}|$ and θ_{23}** were studied by atmospheric/long-baseline experiments.

  $|\Delta m^2_{32}| = (2.32\,^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.95$

ν Oscillation - appearance

- At present, remaining unknown parameters include
  the CP violation phase δ_{CP}, and
  mass hierarchy, sign of
  Δm^2_{32} ($\sim\Delta m^2_{31}$) $= m^2_3 - m^2_2$.
- The ν_e appearance probability contains δ_{CP} term, and Δm^2_{31} term.



$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$
$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta_{CP}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

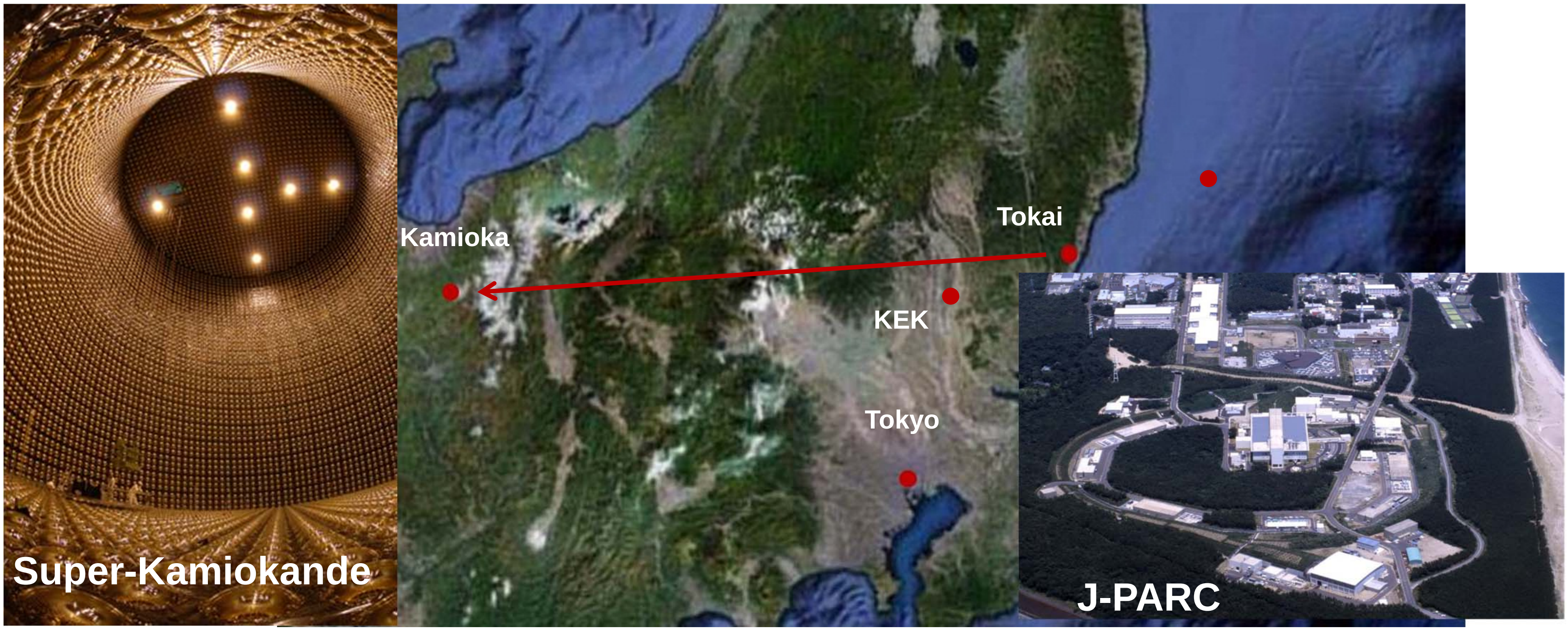
- **Appearance of electron neutrino events can determine $\sin^2 2\theta_{13}$. It will also provides constraints on δ_{CP} and mass hierarchy.**
- **Disappearance of muon neutrino events as well as distortion of the energy spectrum can determine $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ precisely.**

In T2K…

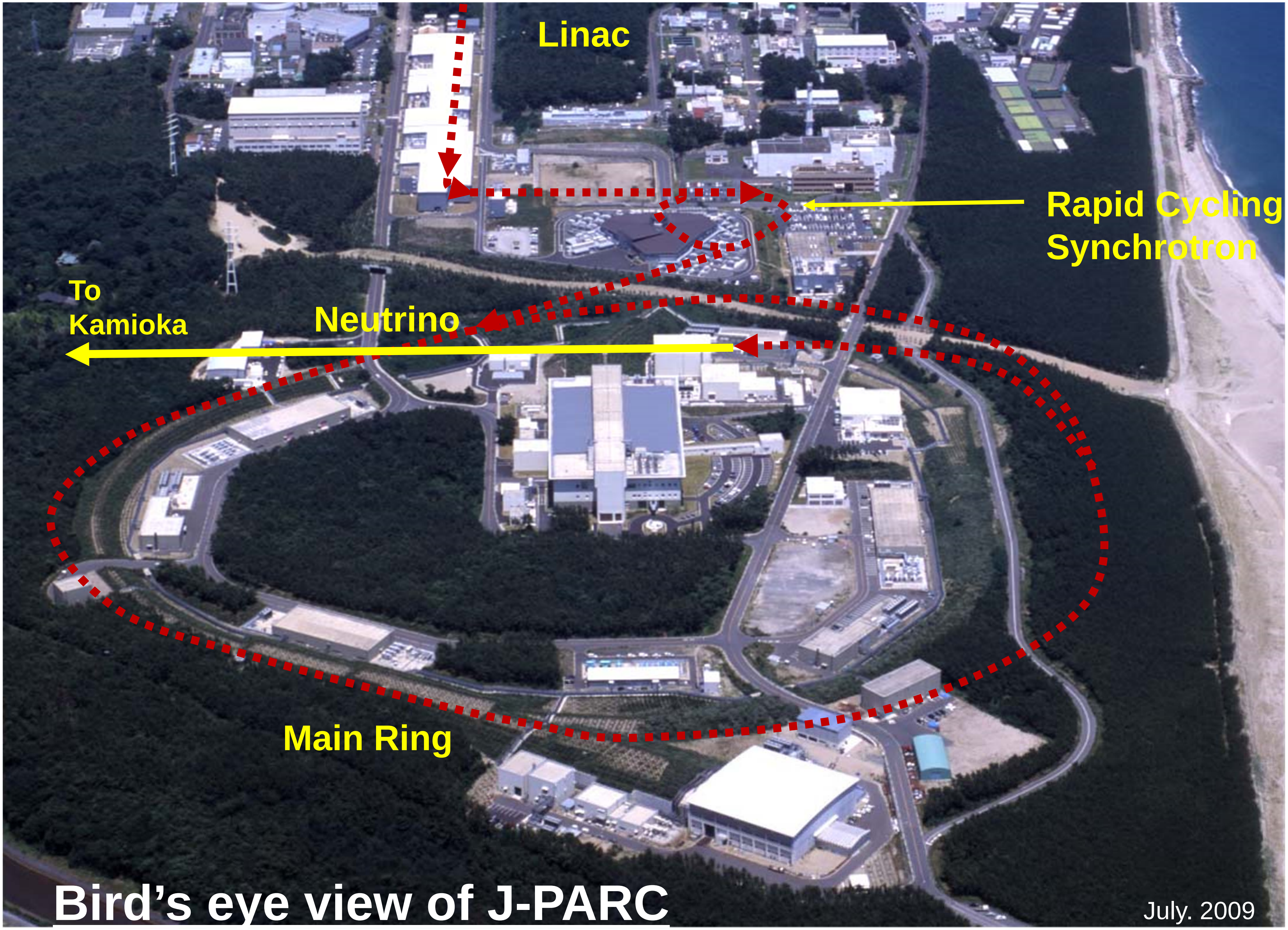
- Appearance of electron neutrino events can determine **$\sin^2 2\theta_{13}$**. It will also provides constraints on δ_{CP} and **mass hierarchy**.

- Disappearance of muon neutrino events as well as distortion of the energy spectrum can determine **$|\Delta m^2_{32}|$** and **$\sin^2 2\theta_{23}$** precisely.

T2K experiment

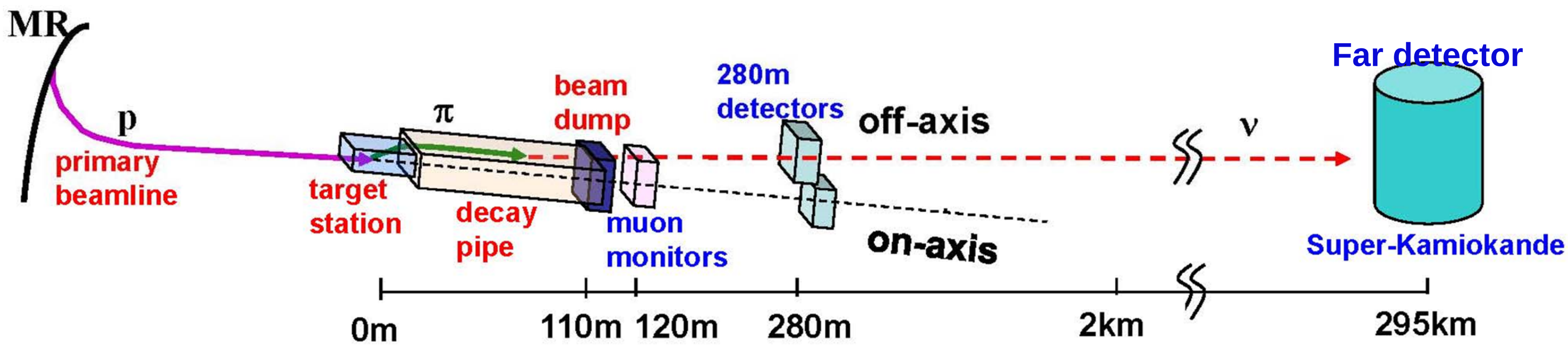


- Second generation long-baseline neutrino-oscillation experiment; from Tokai to Kamioka. The experiment started in 2009.
- High intensity almost pure ν_μ beam from J-PARC is shot toward the Super-Kamiokande detector 295km away.



Bird's eye view of J-PARC

T2K Beam line and Detectors



Beamline

- Primary beamline
- Target station/focusing horns
- Decay Pipe
- Beam dump @ ~110m downstream

Detectors

- Muon monitors@ ~120m
- Near detectors@ ~280m
- Far detector@ 295km (Super-Kamiokande)

Off-axis beam : the center of the beam direction is adjusted to be 2.5º off from the SK direction.

Off-axis beam (2.5°) peak energy~0.6 GeV

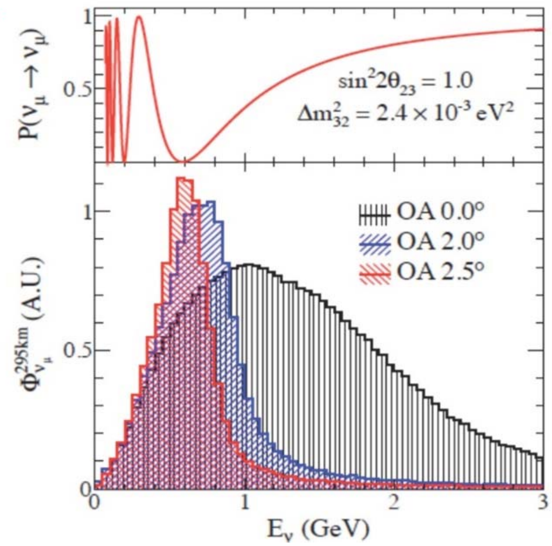
Merits of the off-axis beam are:

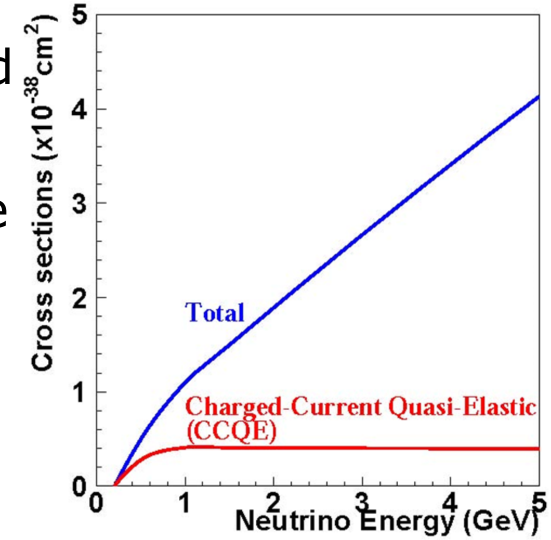
●The neutrino energy peak agrees with the oscillation maximum. Neutrinos oscillate effectively.

●High energy (> 1 GeV) neutrinos are suppressed.

- Neutrino energy spectrum is calculated from CCQE events; ν_μ **+ n ⇢** μ **+ p.**
  Fraction of CCQE events is small in high energy range and some of non-CCQE events are serious background for the CCQE selection.
- Neutral Current (NC) π^0 events are background for the ν_e appearance search.
  NCπ^0 events are reduced by the suppression of high energy neutrinos.

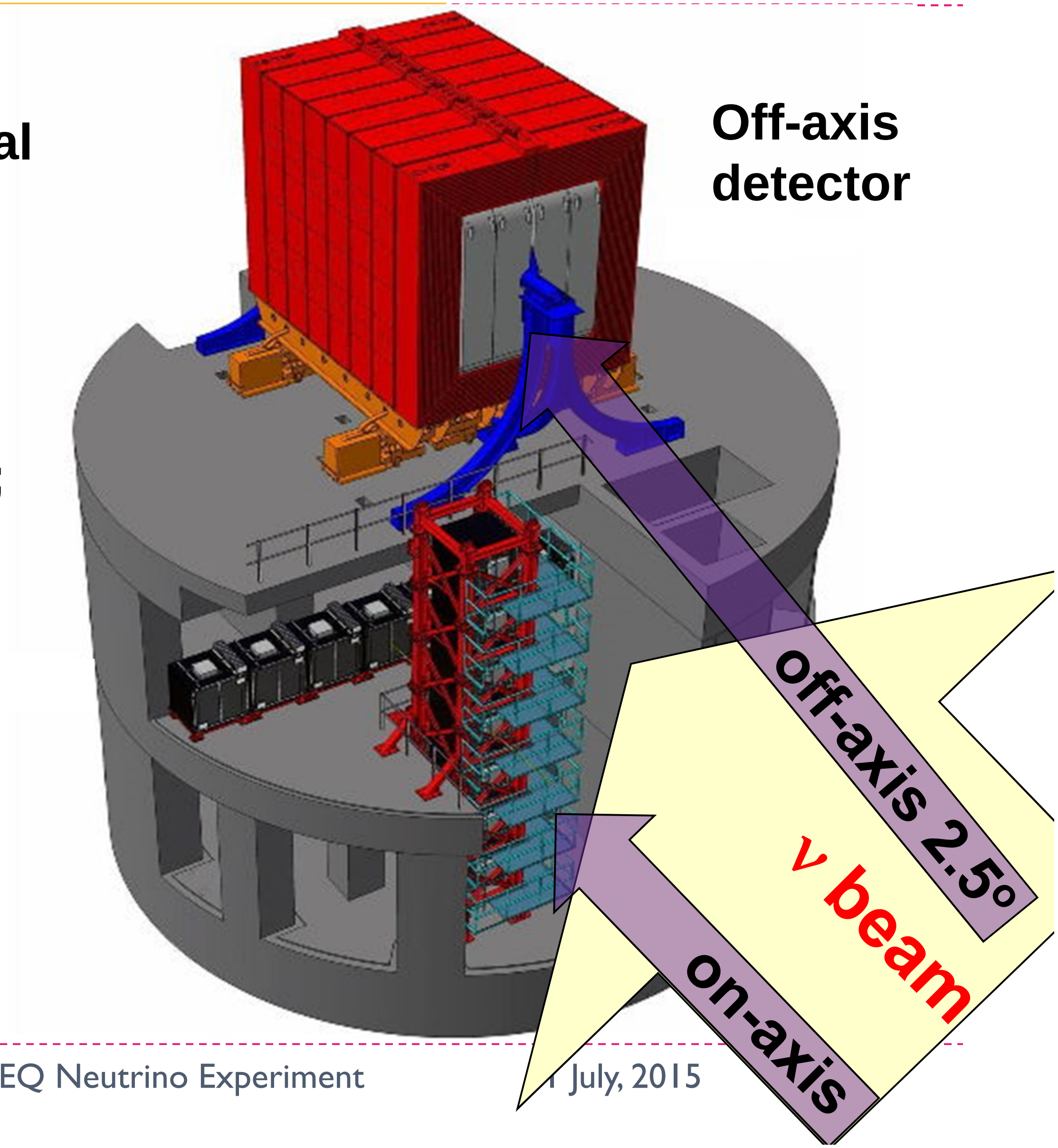
●Water Cherenkov detector has better performance for single charged particle events.





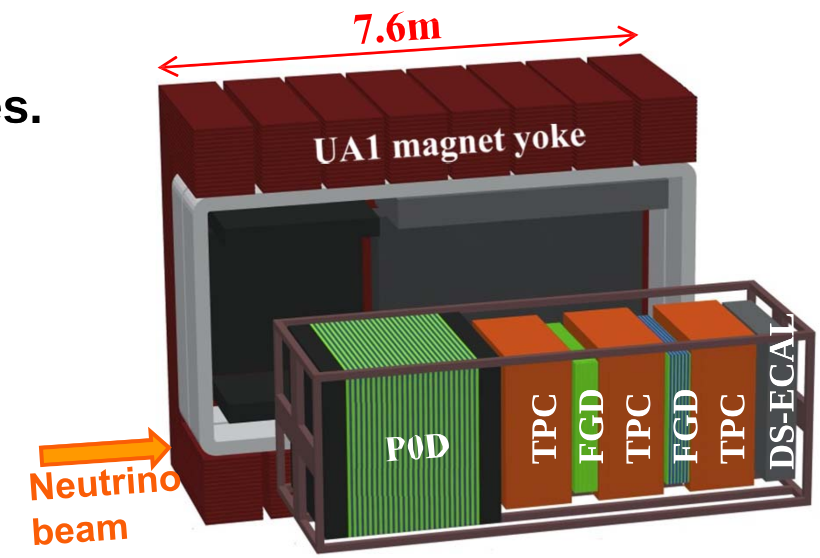
ND-280 near detector

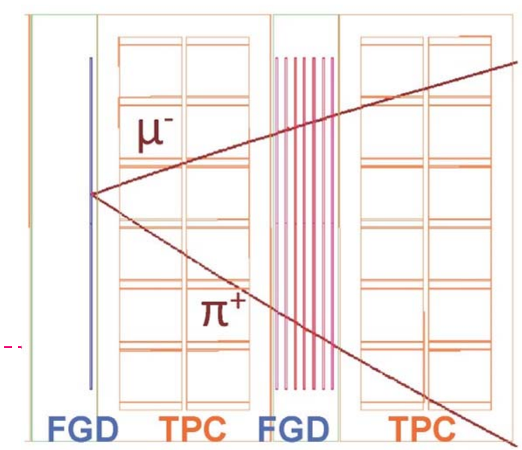
- **The detectors were made in the underground experimental hall, 33.5m depth and 17.5m diameter.**
  It is located at 280m downstream from the target.
- **Two detectors were installed; they are On-axis Detector in the direction of the neutrino beam center, and Off-axis detector in the direction of Super-Kamiokande.**



Near Detectors at 280m downstream

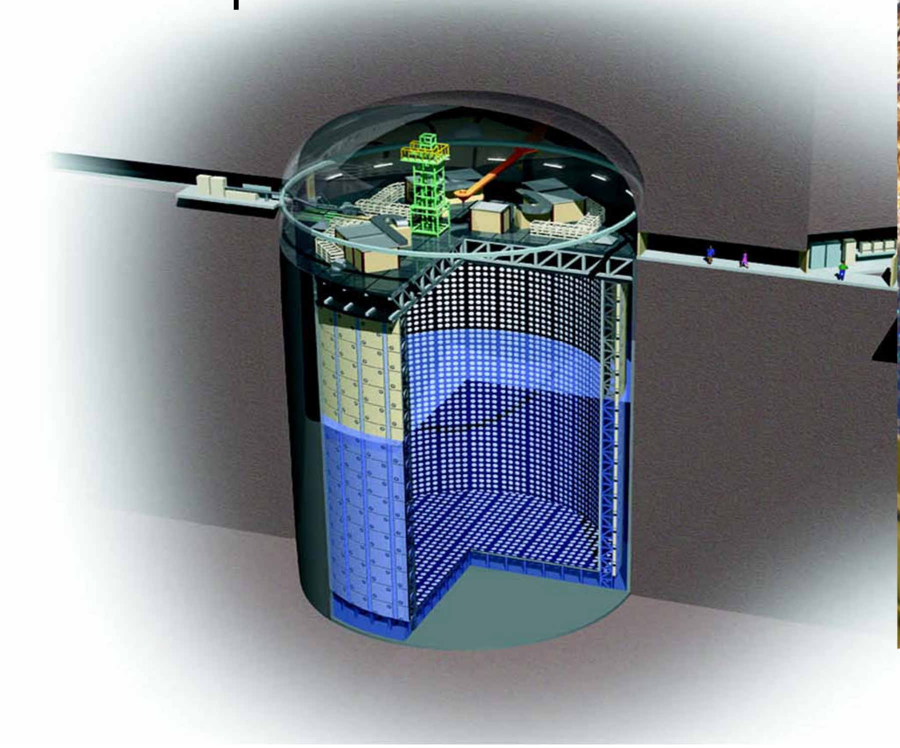
- ND280 is made from several components.
- 2 FGDs (Fine-Grained Detectors) consist of scintillators and water as target material.
- 3 gas-filled TPCs (Time Projection Chambers) record track of charged particles.
- All components are in 0.2T of magnetic field. The magnets were previously used in UA1 and NOMAD.
- Charged particles are bent by the magnetic field. The curvature of the track recorded by TPC are used to determine the momentum of the particles.
- Neutrino flux as well as neutrino interactions can be studied from the reconstructed track information.
- Other components are P0D (π^0 detector), ECAL(Electromagnetic CALorimeter) and SMRD(Side Muon Range Detector).

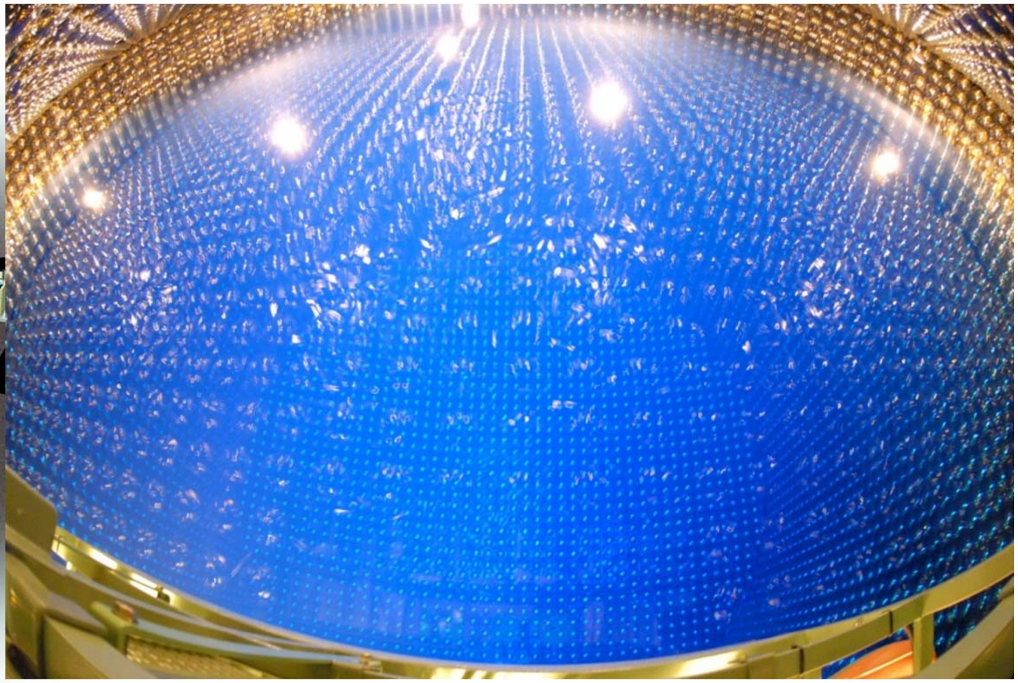




Far detector (Super-Kamiokande (SK))

- 50kt water Cherenkov detector with 11129 20-inch diameter PMTs. The fiducial volume of the detector is 22.5kton.
- Located at 1000m underground in Kamioka mine, Japan. The distance from the J-PARC is 295 km.
- The experiment started in 1996, and SK-IV(after electronics replacement) is in operation since 2008.

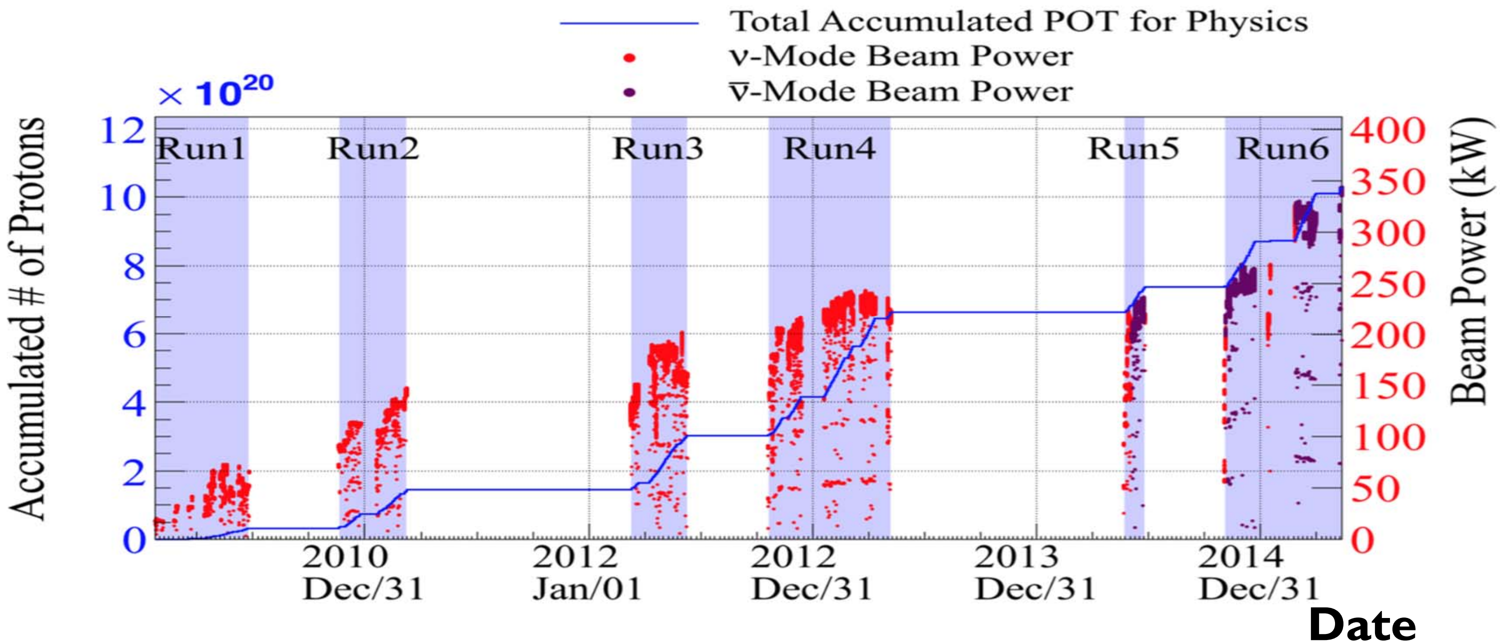




T2K Collaboration

The T2K collaboration includes about 500 physicists from 11 countries (Canada, France, Germany, Italy, Japan, Poland, Russia, Spain, Switzerland, UK, USA).

History of the T2K beam

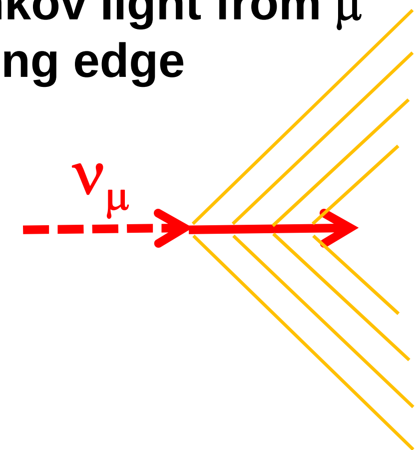


- Physics run started in Jan. 2010. In May 2015, the maximum beam power achieved is ~345kW.
- In June 2014, anti-neutrino beam has been started by changing the current direction of the magnetic horns.
- Integrated pot (protons on target) until Mar. 2015 are:
  10.12×10^{20} (total) = 7.00×10^{20} (neutrino) + 3.12×10^{20} (anti-neutrino).

μ/e identification in Super-Kamiokande

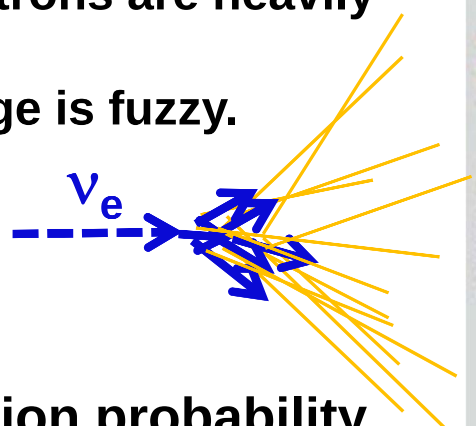
ν_μ μ

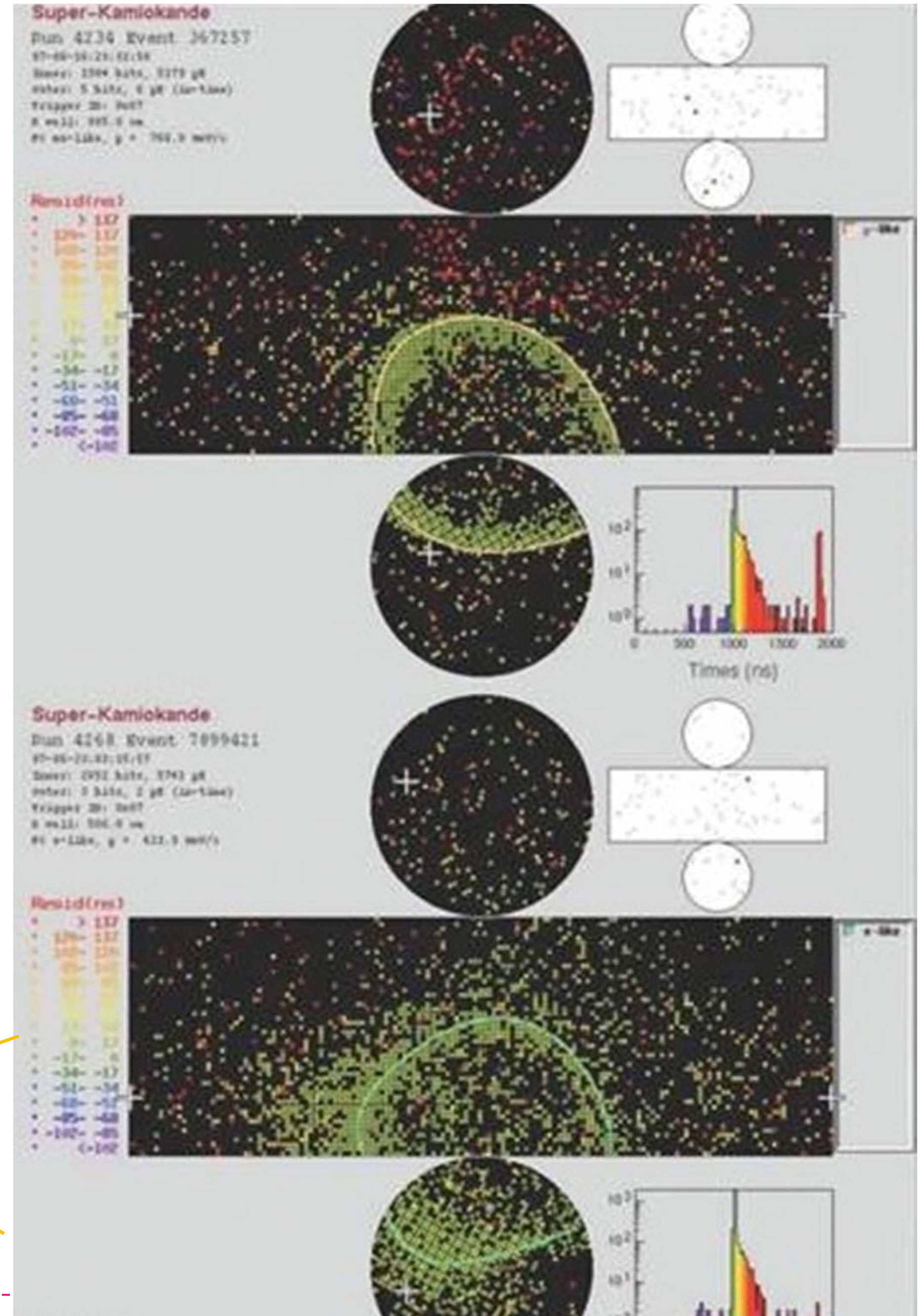
Only direct Cherenkov light from μ
Clear Cherenkov ring edge



$\nu_e \rightarrow$ e

Cherenkov light from e-m shower.
Electrons and positrons are heavily scattered.
Cherenkov ring edge is fuzzy.





Figures from http://hep.bu.edu/~superk/atmnu/

μ/e misidentification probability is less than **1%**.

Results of Event Selection

Examine Particle ID of 1 ring events

ν_μ selection

- μ-like PID
- p_μ > 200 MeV/c
- Michel electron 1 or 0

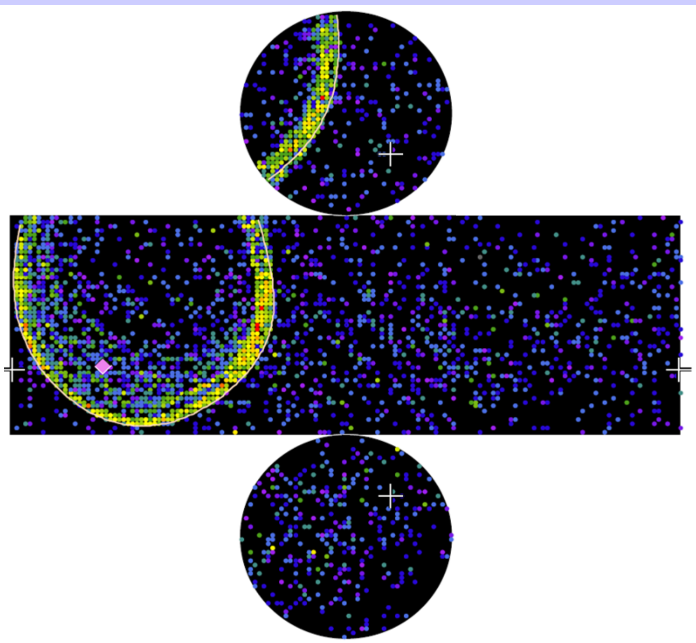
Data : 120 events
Expected: 446±23(sys.) events
(no oscillation)

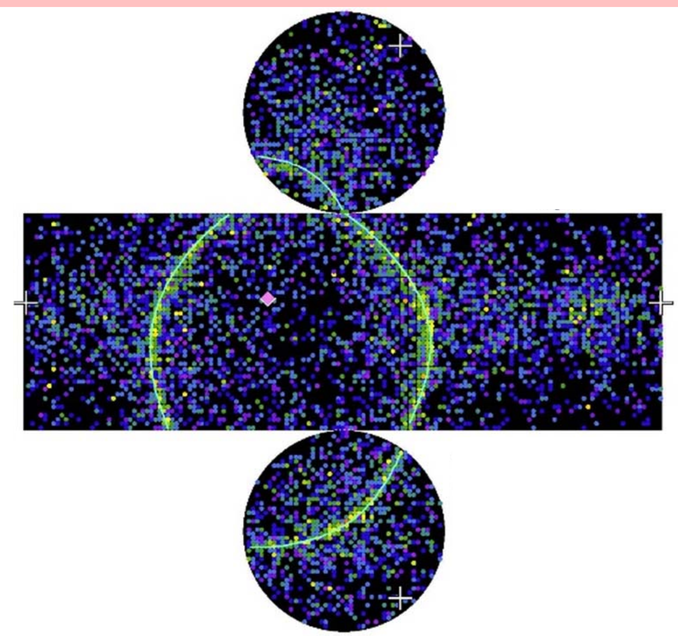
ν_e selection

- e-like PID
- p_e > 200 MeV/c
- Michel electron 0
- E_{rec} < 1250MeV
- π^0 rejection

π^0 rejection : Forced 2^{nd} ring is assumed. Invariant mass and likelihood for π^0 are examined.

Data : 28 events
Expected: 4.9±0.6(sys.) events
(no oscillation)





Results
ν_μ disappearance

- Disappearance of muon neutrino events as well as a distortion of neutrino energy spectrum is found.
- Best-fit oscillation parameters are calculated to be

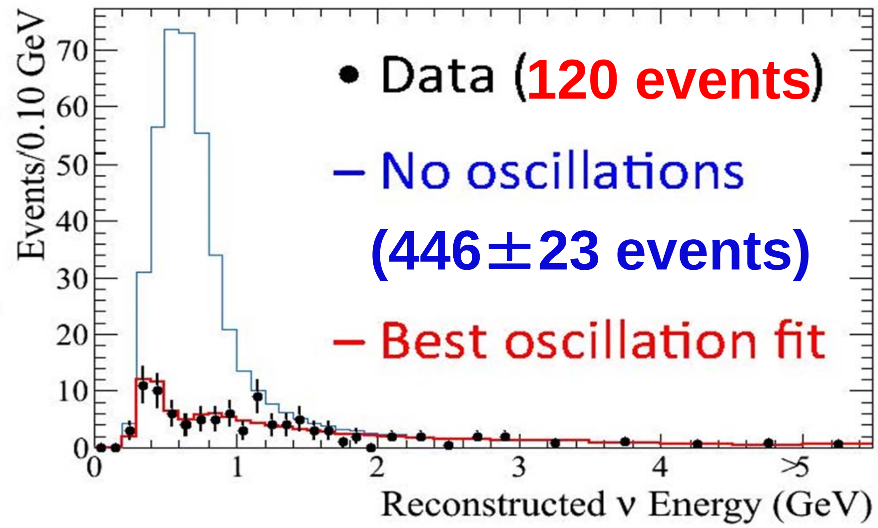
$$\Delta m^2_{32} = (2.51 \pm 0.10)\times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

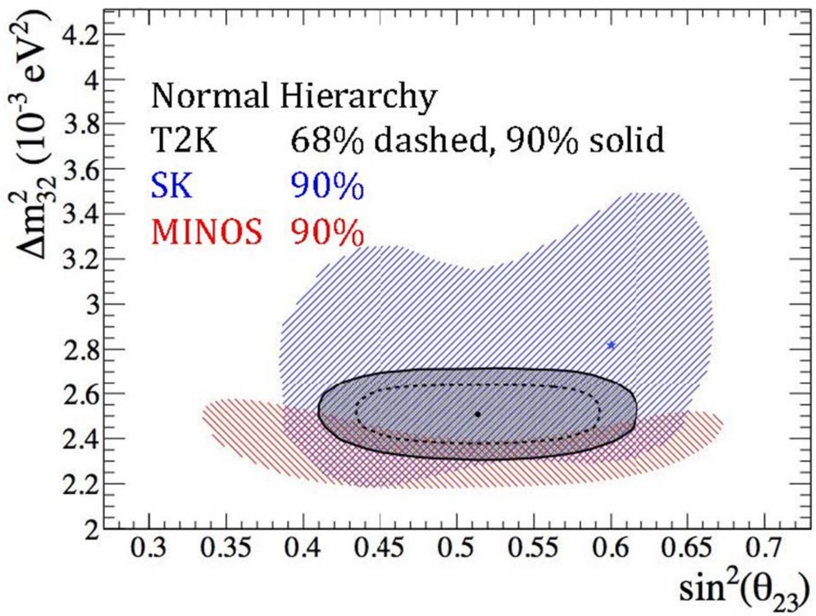
for normal hierarchy, and

$$\Delta m^2_{13} = (2.48 \pm 0.10)\times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.511 \pm 0.055$$

for inverted hierarchy.

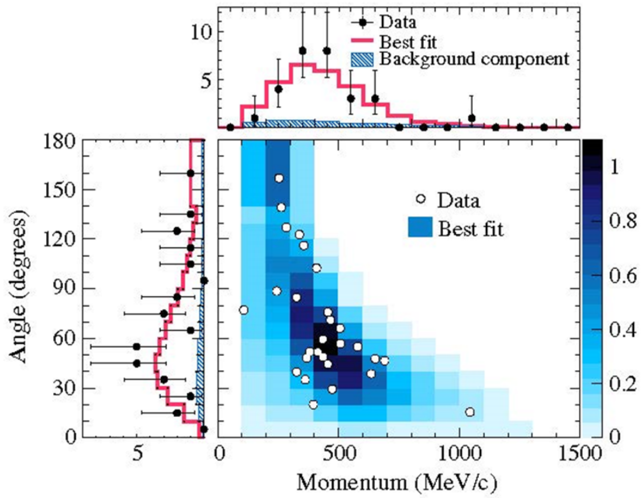
- These results give most stringent constraints for $\sin^2\theta_{23}$

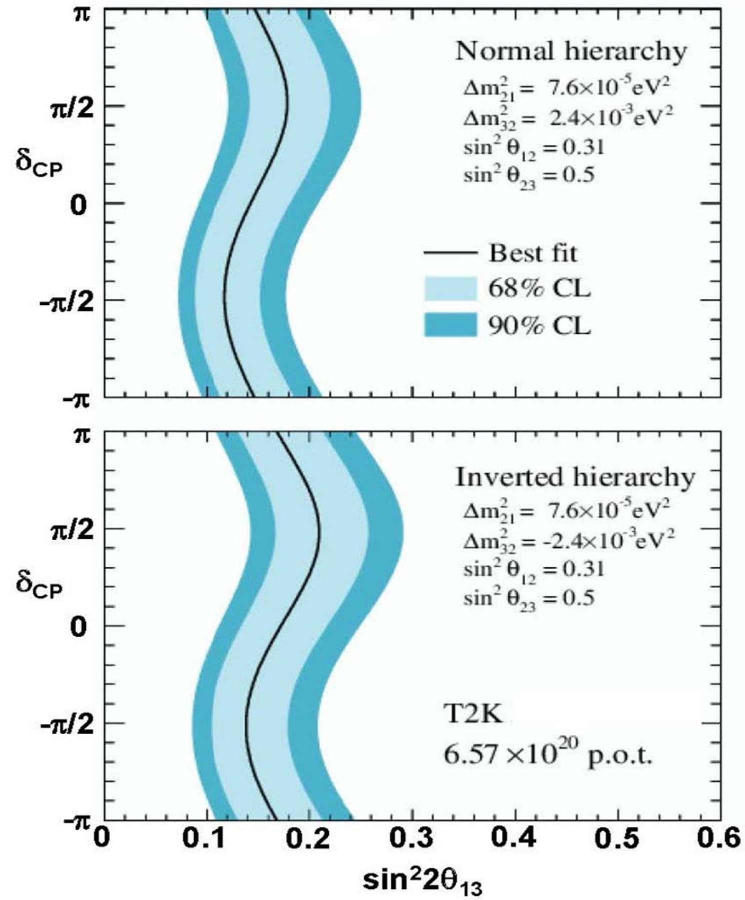




Results-ν_e appearance

- Where expectation for no oscillation is 4.9±0.6(sys.) events, 28 events are found. The signal is **7.3σ** and it is certainly discovery.
- **In (p_e,θ_e)** distr, maximum likelihood analysis finds the 90% C.L. region in **$\sin^2 2\theta_{13} - \delta_{CP}$**





- The 68% C.L. intervals for **$\sin^2 2\theta_{13}$** are

$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ (NH) and

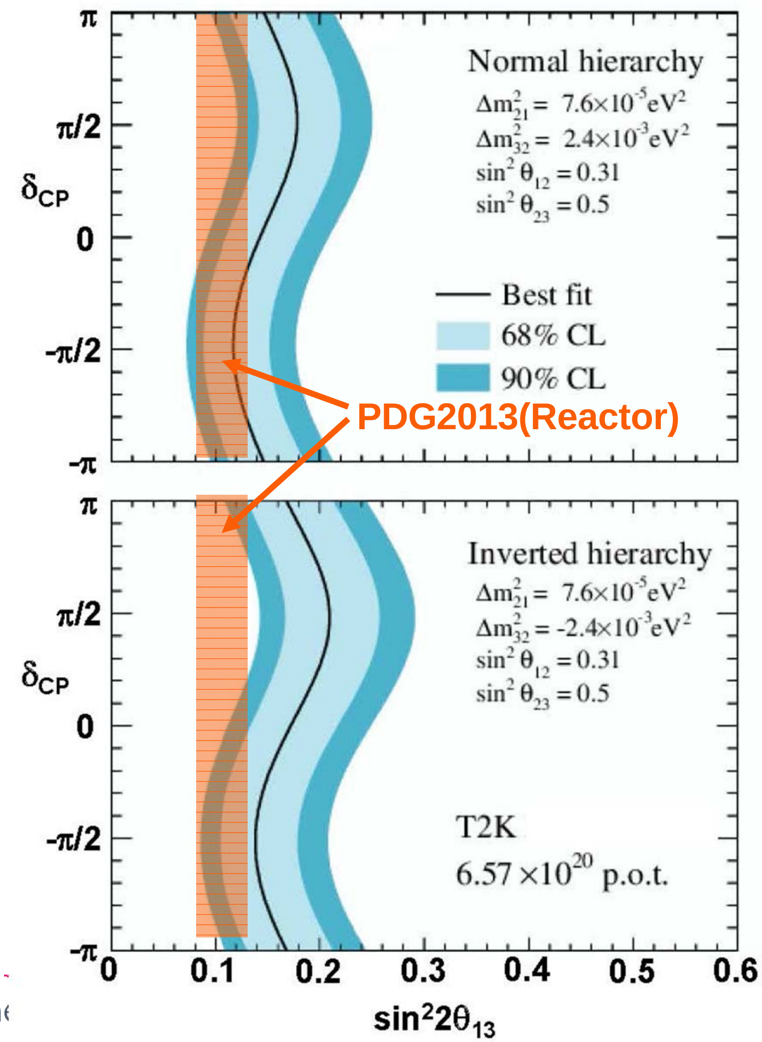
$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$ (IH) for $\delta_{CP} = 0$.

Combined ν_e and reactor results

- The T2K results are combined with constraints from reactor experiments (Daya Bay, Reno and Double Chooz);
  $\sin^2 2\theta_{13} = 0.095 \pm 0.010$ **(PDG2013).**
- It seems that negative δ_{CP} with normal hierarchy is favored.
- From more complicated and exhaustive statistical analysis,

0.146π	<	δ_{CP}	<	0.825π	(NH)
-0.080π	<	δ_{CP}	<	1.091π	(IH)

  are excluded with 90% C.L.
- The results are hints towards $\delta_{CP} \sim -\pi/2$ and normal hierarchy.



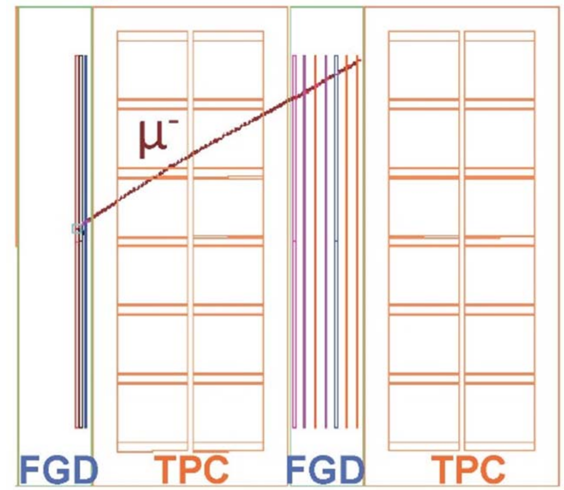
Problems

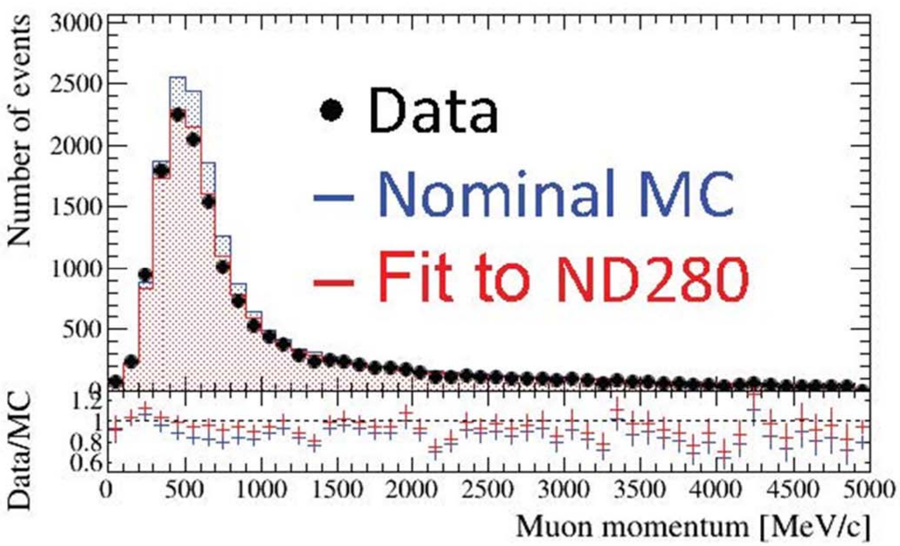
- How do you measure beam energy?
  - Choose topology that guarantees interaction (e.g. CCQE) and measure energy with kinematic equations (T2K, MiniBooNE)
  - Measure all particles in final state (MINOS, DUNE?)
- How do you predict neutrino spectrum?
  - Extrapolate results from near to far detector
  - How many ν_e in beam if you are searching for $\nu_\mu \rightarrow \nu_e$?
  - Calculate with Monte Carlo.
- How do you know backgrounds?
  - Measure if possible (NCπ^0 in near det), use Monte Carlo
- What about the fact that ν spectrum very different at near and far detectors?
  - Monte Carlo

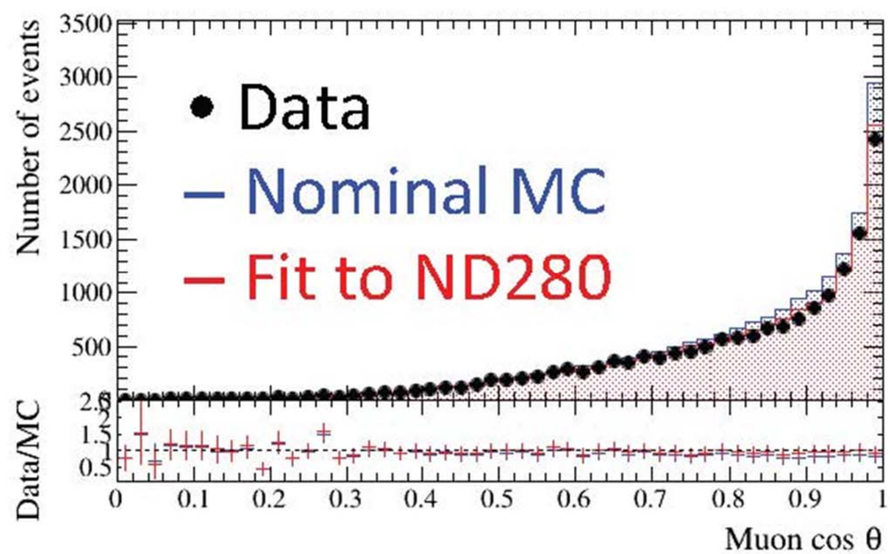
Near detector constraints

CCQE : Charged Current Quasi Elastic
$CC1\pi$: Charged Current 1π resonant prod
CC_{dis} : Charged Current Deep Inelastic Scattering

- CCQE events, $CC1\pi$ events, and CC_{dis} events are selected separately based on track topologies in ND280 FGD/TPC.
- $\mathbf{p}_{\mu}$ and $\mathbf{cos}\theta_{\mu}$ distributions (data and MC) compared. All systematic errors related to cross sections and neutrino fluxes are adjusted from the comparison.
- Excellent agreement after parameter adjustment. The adjusted parameters can be also applied for SK.

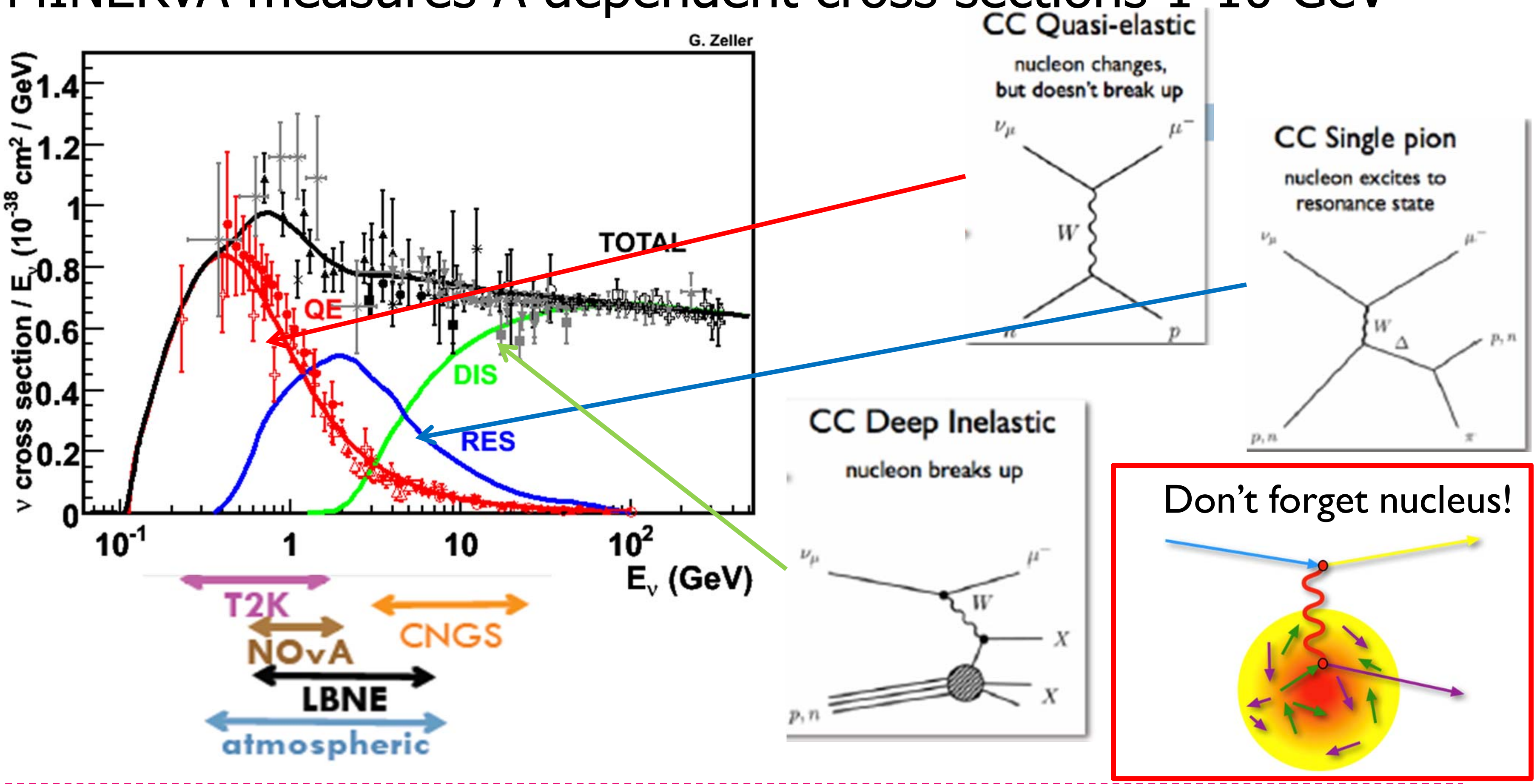






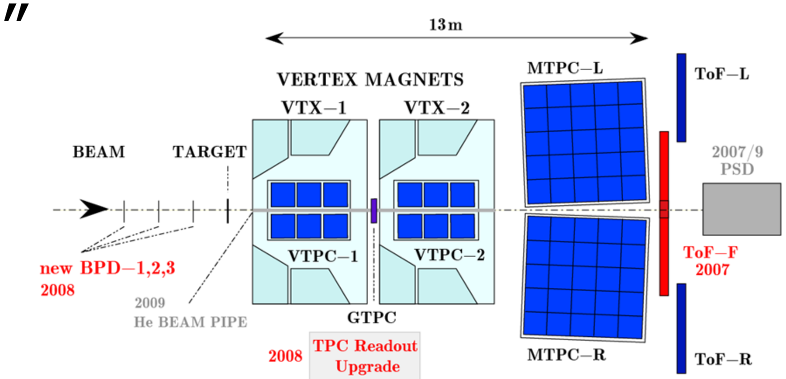
Cross section definitions
See Formaggio & Zeller RMP 2012

- Most nucleon data from bubble chambers (low statistics)
- MINERvA measures A dependent cross sections 1-10 GeV

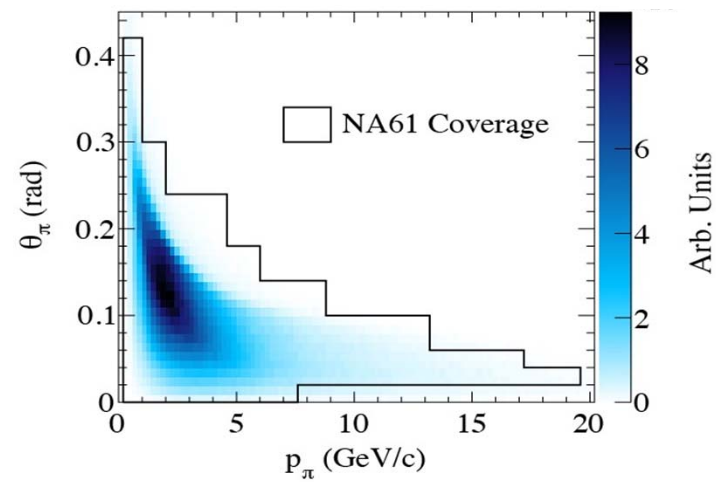


Verifying MC calculation of beam flux

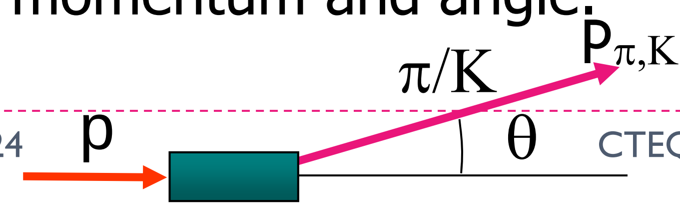
- Some of T2K members join CERN NA61/SHINE : "Study of hadron productions in hadron-nucleus and nucleus-nucleus collisions at CERN SPS"



- The energy of the proton beam is adjusted to the T2K proton beam, 30GeV. Thin (2cm) carbon plate is used as target. The carbon material is same as T2K



- Production of pions and kaons are precisely measured by TPC and TOF. Their fluxes are measured as a function of momentum and angle.

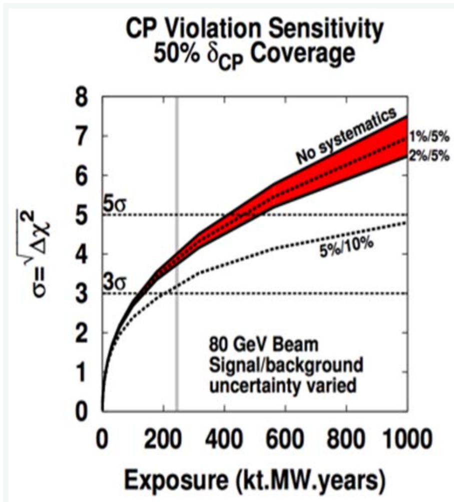


Systematic errors & backgrounds

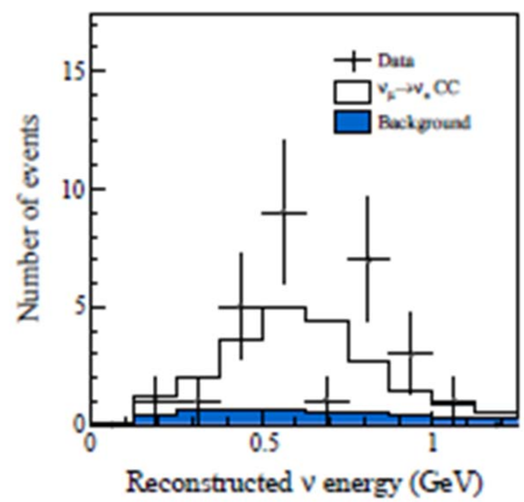
T2K syst errors for $\nu_\mu \rightarrow \nu_e$ (2014)

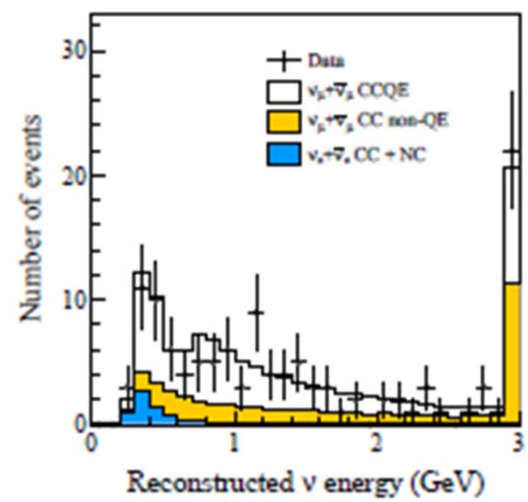
Source of Uncertainty	Est. stan. dev.
Cross section (MC)	**4.9%**
Cross section (ND280), Flux	2.7%
Far Det, FSI	**5.6%**
Oscillation parameters	0.2%
TOTAL	8.1%

DUNE estimated syst errors



T2K data with estimated background



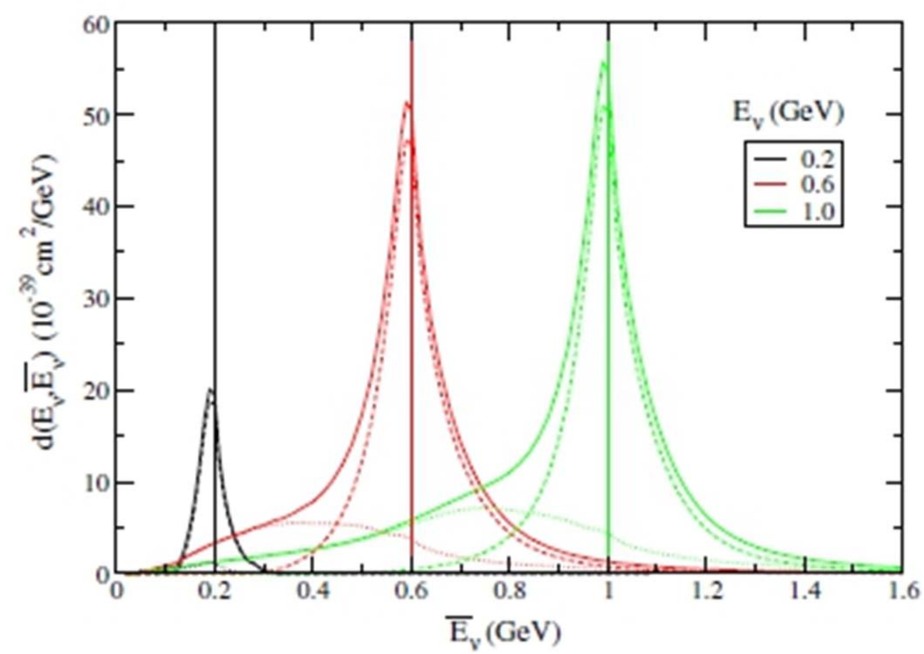


Measuring beam energy with CCQE (T2K)

- Experiments identify reaction with topology, calculate Eν assuming single nucleon at rest. *Ambiguities!*

$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right) E_\ell - \left[\left(M_n - E_B\right)^2 + m_\ell^2 - M_p^2\right]}{2\left[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)\right]}$$

- What if principal interaction was pion production and pion was absorbed?
- What if principal interaction was with correlated nucleons (MEC)? (plot from Martini, PRD87,013009 (2013)
- *Nuclear model essential!*



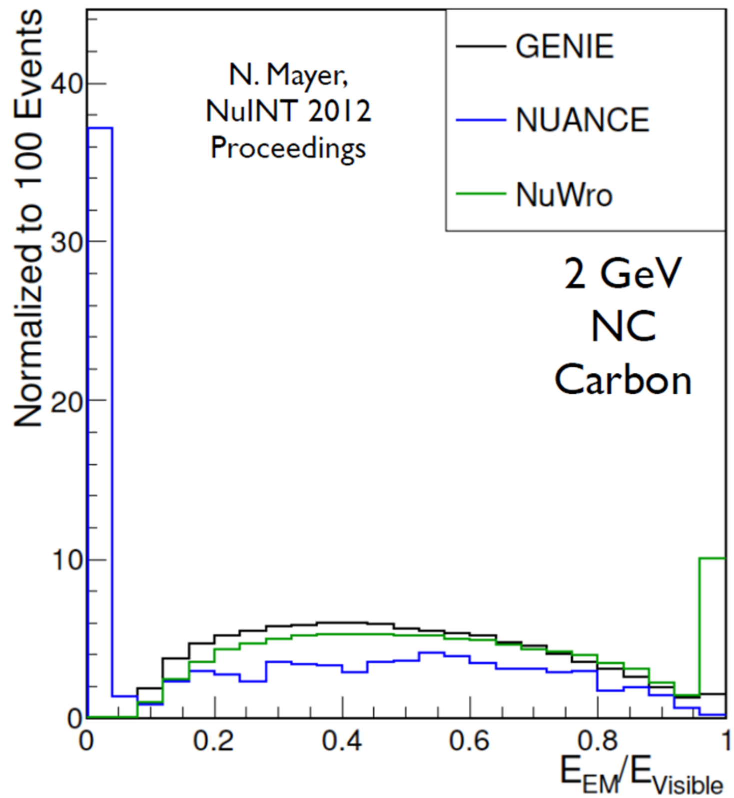
Jorge Morfin's summary (it's the nucleus!)

- The events we observe in our detectors are convolutions of:
  $Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

- $Y_{c\text{-like}}(E)$ is the event energy and channel / topology observed in the detector, not necessarily that which is produced. It is called c-like since it appears to be channel c but may not have been channel c at interaction.
- $\phi(E)$ is the energy dependent neutrino flux that enters the detector. With traditional meson-decay-source neutrino beams we can, with considerable effort, estimate the incoming neutrino energy distribution to ≤ 10% absolute and ≤ 7% energy bin-to-bin accuracy. **Significant contribution to systematic**
- $\sigma_{c,d,e..}(E' \geq E)$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.** Form factors are modified within a nucleus compared to a nucleon. **Significant contribution to systematics**.
- $Nuc_{c,d,e..\rightarrow c}(E' \geq E)$ **– Nuclear Effects.** In general the interaction of a neutrino with energy E' creating initial channel d,e… can appear in our detector as energy E and channel c.
  - **Nuclear Effects** – a migration matrix that mixes produced/observed channels and energy. ν and $\bar{\nu}$ **quite different.** **Significant contribution to systematics**.

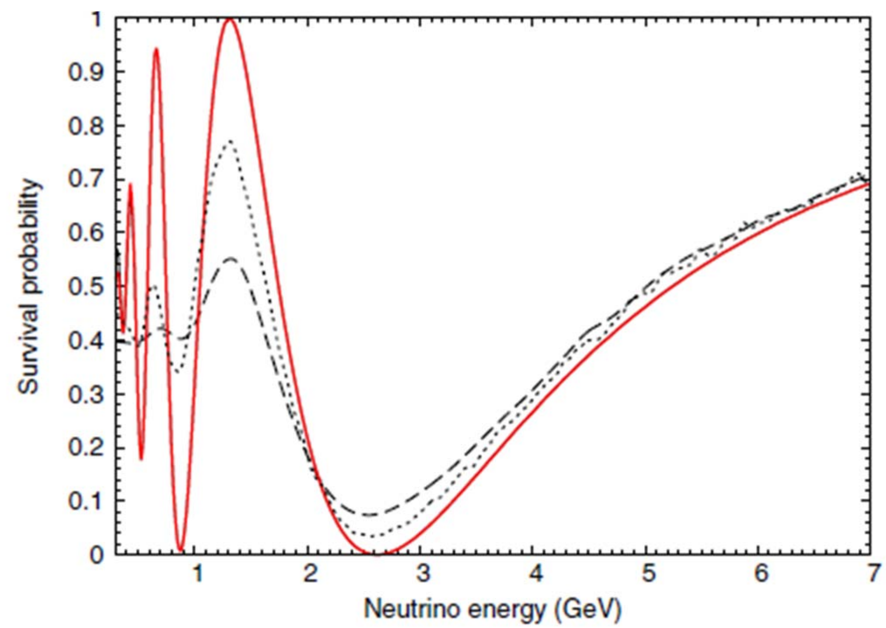
example

- DIS event at E_ν=8 GeV
- Principal interaction result is μ^-, $2\pi^-$, $2\pi^+$, $2\pi^0$, p.
- After FSI, final state is μ^-, $1\pi^-$, $2\pi^+$, 4γ, 2p, 3n.
- Through π^- absorption and π^+ charge exchange, energy shifts toward neutral and more baryons.
- Cerenkov detectors don't see hadrons and scintillators and calorimeters don't see low energy hadrons or neutrons.
- Therefore, the energy could be measured as 4 GeV unless Monte Carlo can make up the difference.
- NuINT conferences have useful studies comparing theory and generators.



ν interaction needs

- Measurements (or calculation) of all processes at higher ν energy
- How they can mimic desired signal in detector
- Don't forget detectors are large and contain variety of materials, don't forget nuclear effects!
- Here's worst case calculation for DUNE using CCQE hypothesis. (Mosel, PRL 2014)
- [H bubble chambers look really good now, but safety considerations make this impossible.]



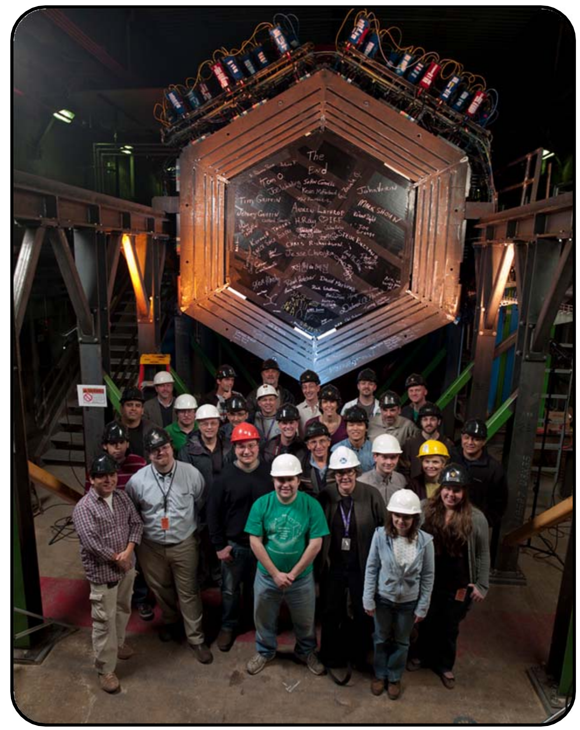
MINERvA

- Cross section experiment at FNAL (NuMI beam line)
- Taking data 2009-13 with $<E_\nu>$~4 GeV, now 7 GeV
- Fine-grained scintillator

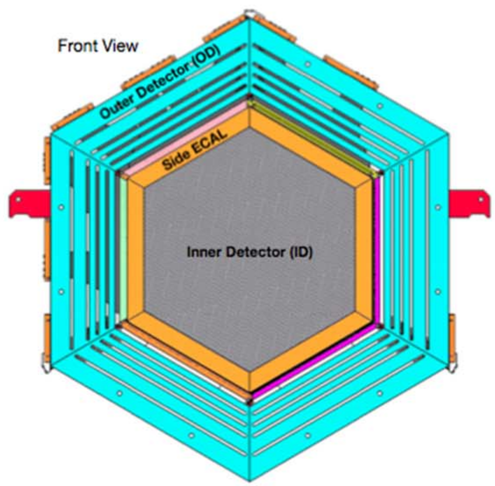
~60 collaborators from particle and nuclear physics

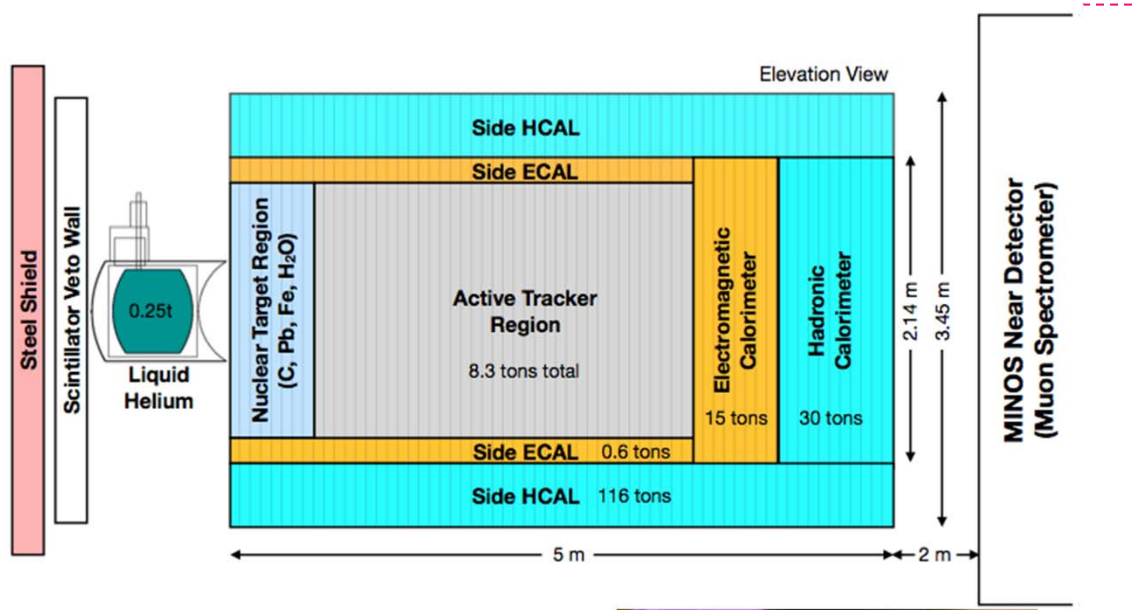
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago

Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
College of William and Mary



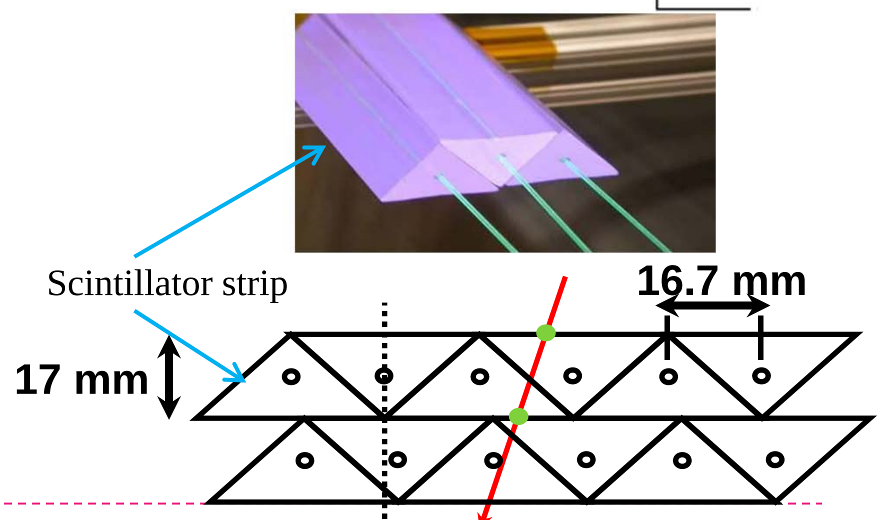
MINERvA detector



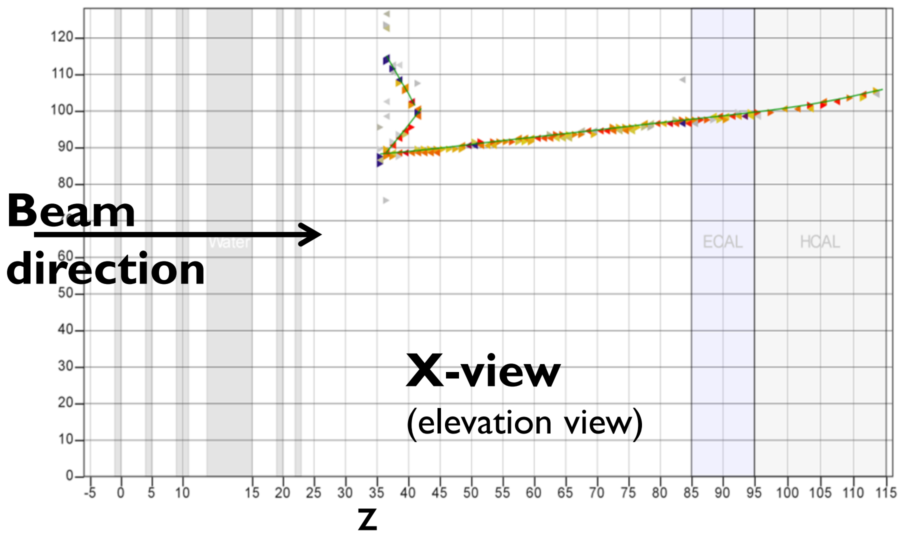


Central region is **finely segmented scintillator tracker**

~32k plastic scintillator strip channels total



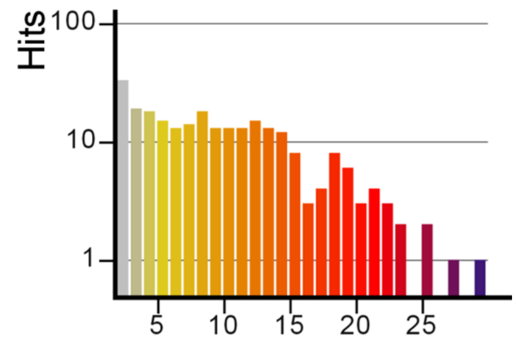
Sample event (3 views for 3-d track)

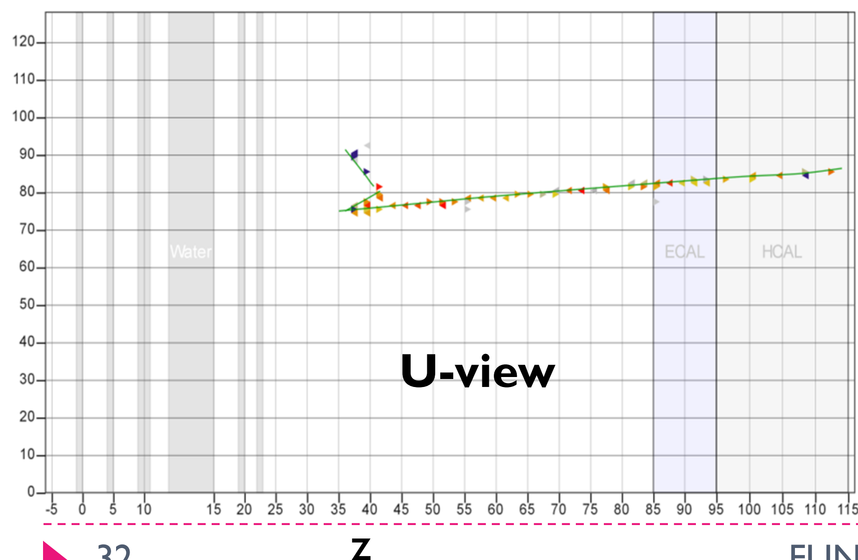


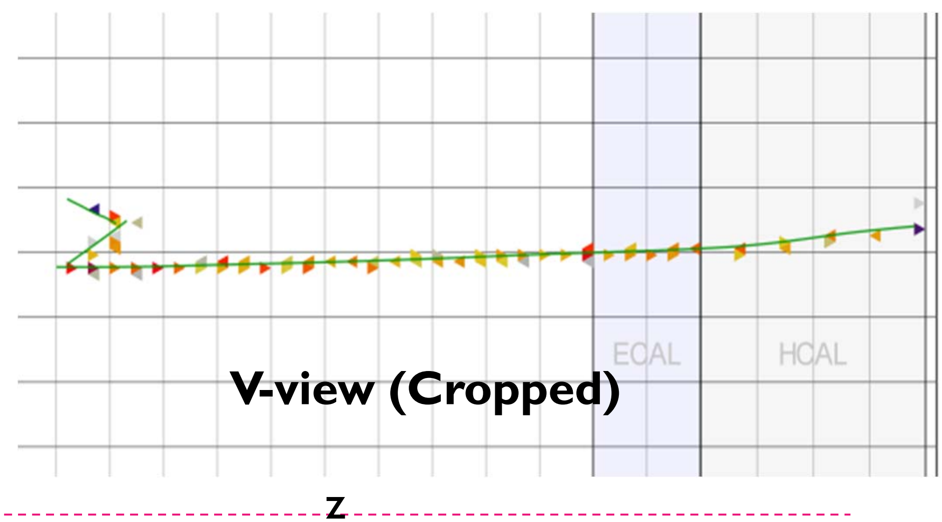
Data Candidate: Scattering π^+

Look for vs. z

1. No energy deposit
2. Vertex
3. Significant deposit



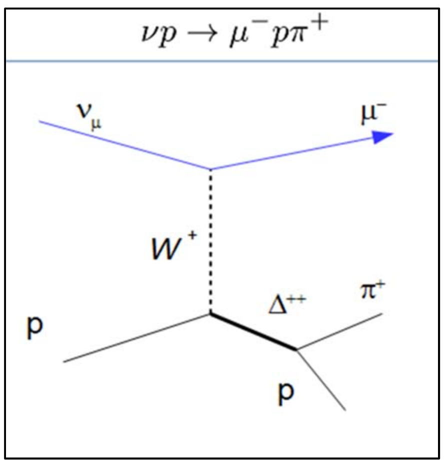




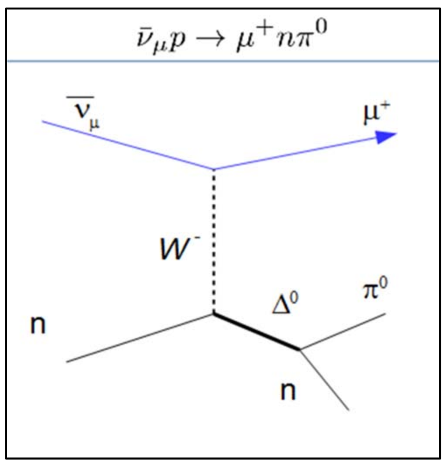
Focus here on 2 recent results for CC Pion production

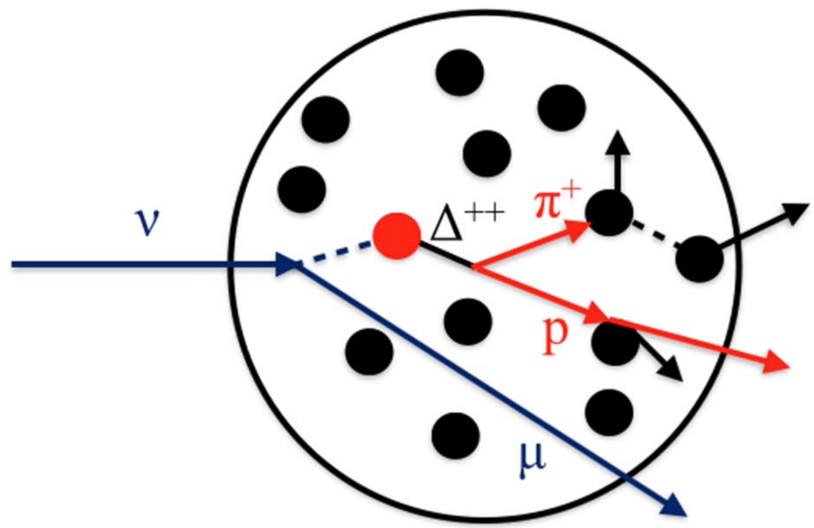
- Important component of Long Baseline expts (T2K, NOvA)
- Sensitive to principal interaction, nuclear medium, and final state interactions (FSI)

Charged-Current Single Charged Pion Production



Charged-Current Single Neutral Pion Production by nubar





Theory primer

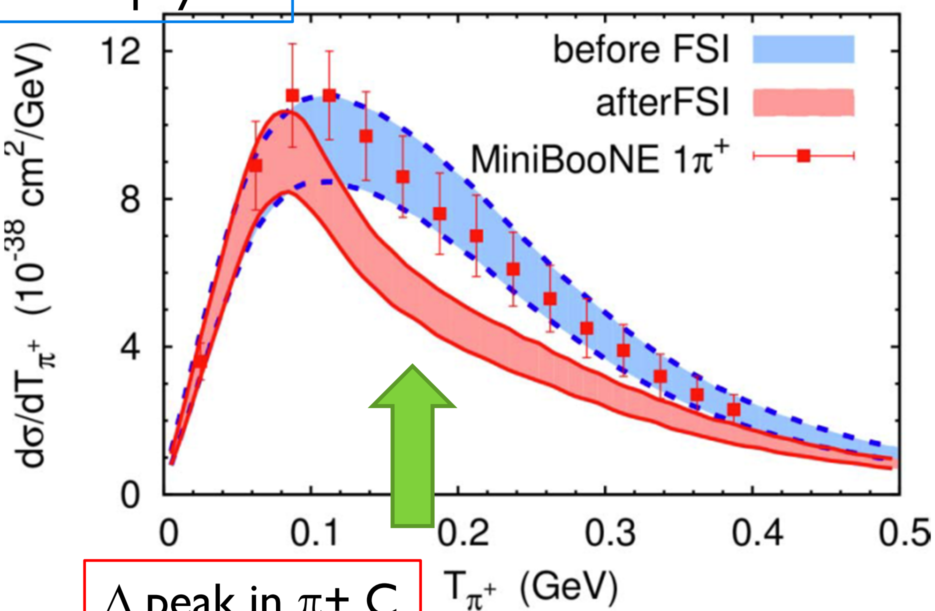
- Best calculations from nuclear theorists with background in electron scattering
  - Best nuclear models, medium corrections, FSI
- Event generators required to simulate experiment
  - Plan, analyze, describe data
  - Contain simplified versions of best theory
  - Developed, maintained by poorly understood, overworked experimenters
  - Better nuclear models are being introduced, but not in any of following plots.

Focus here on 2 recent results from MINERvA for Pion production

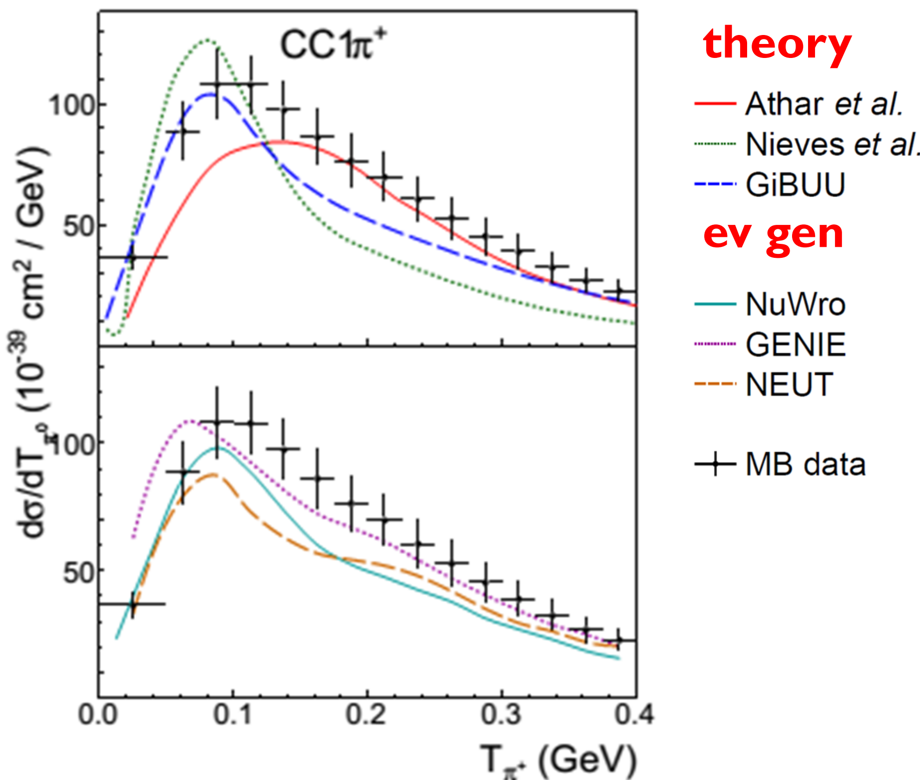
- MiniBooNE cross section results surprising, huge impact
- Do we really understand FSI (detail!)

GiBUU: Best nuclear physics

Data at E_ν~1 GeV



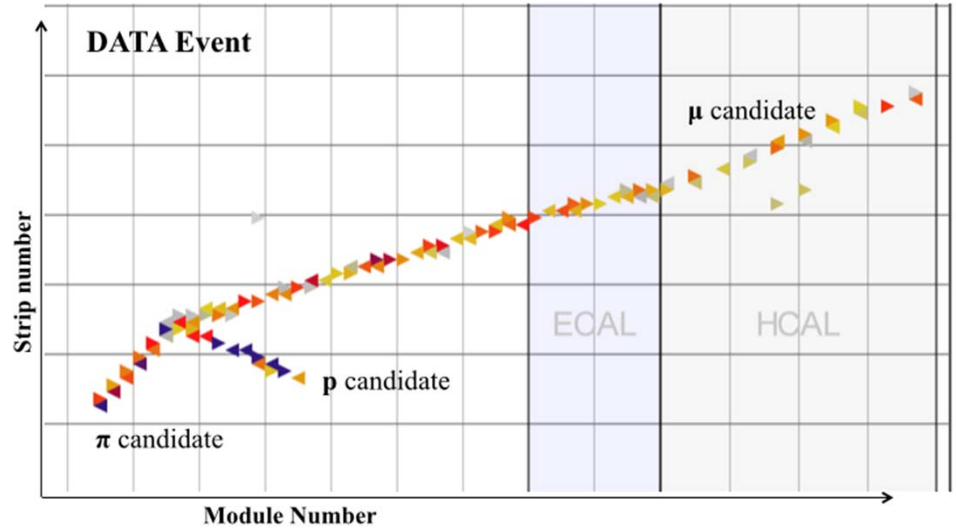
Δ peak in π+ C

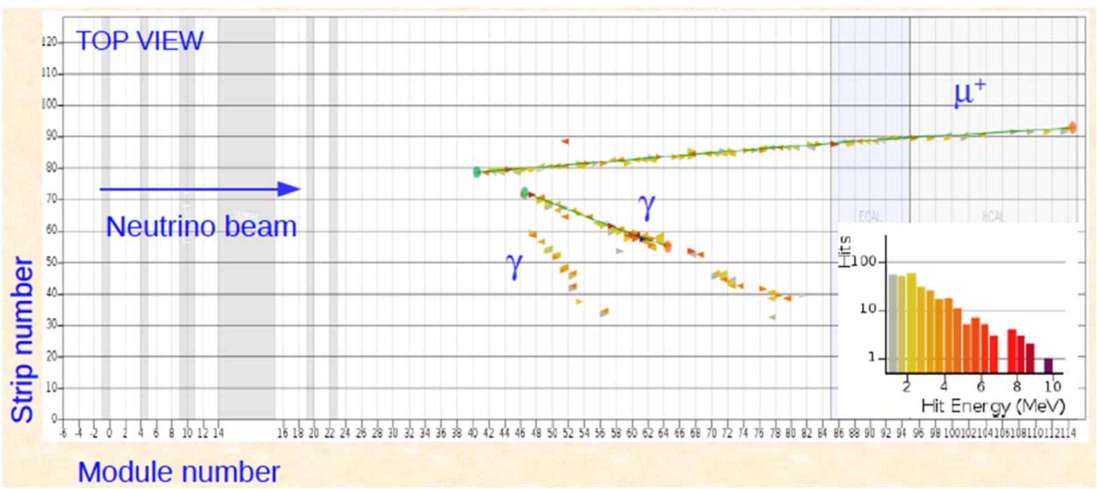


GiBUU: O. Lalakulich and U. Mosel, PRC 87, 014602 (2013)
NuWro: T. Golan, C. Juszczak, J. Sobczyk Phys Rev C80, 15505 (2012)
Nieves: E. Hernanadez, J. Nieves, M.Vicente Vacas, Phys Rev D87, 113009 (2013)

Sample events

- XZ view, one of 3 views
- See charged hadron tracks
- See π^0 if both photons convert to e^+e^-.





Event definitions

- Charged pion
  - μ^- in MINOS
  - $1.5<E_\nu<10$ GeV
  - W(hadronic mass)<1.4 GeV or <1.8 GeV
  - Pion identification (tracking, Michel decay)
- Neutral pion
  - μ^- in MINOS
  - $1.5<E_\nu<20$ GeV
  - γ conversion length>15 cm
  - Di-photon invariant mass $75<M_{\gamma\gamma}<195$ MeV/c^2.
  - W<1.8 GeV or no W cut

Kinematic Equations

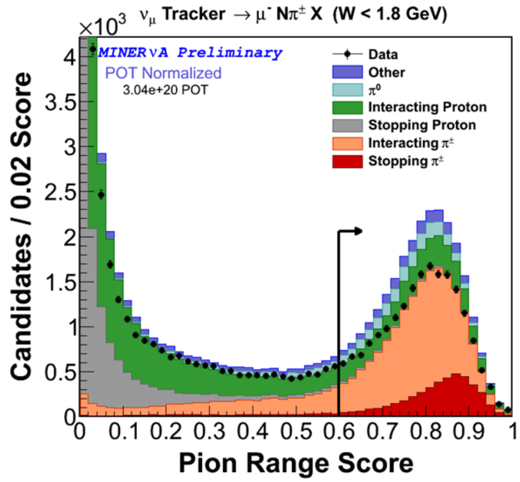
$$E_\nu = E_\mu + E_H \ (E_H \text{ determined calorimetrically})$$

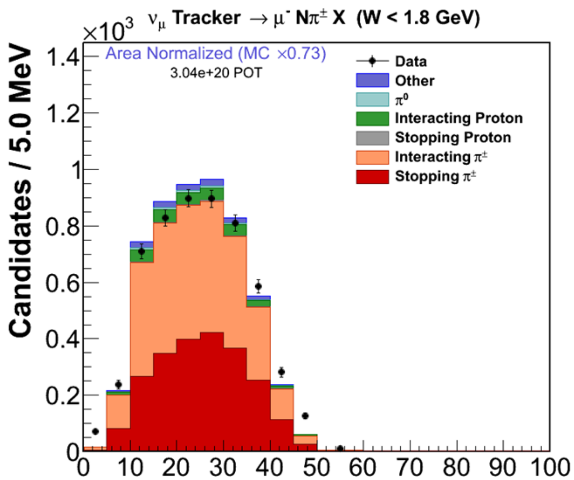
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

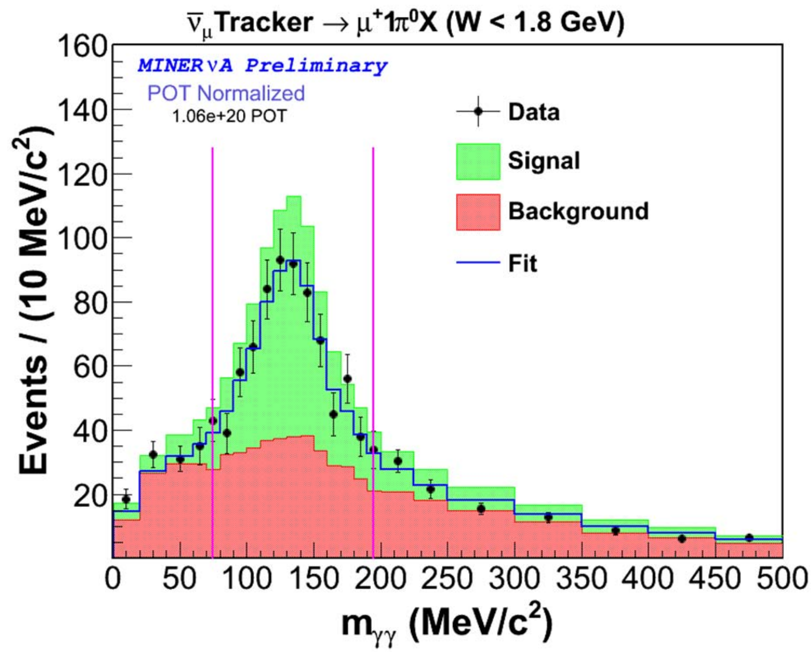
$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \ (m_N \text{ nucleon mass})$$

$$W_{gen} : W_{exp} \text{ w/o the assumption of a nucleon at rest}$$

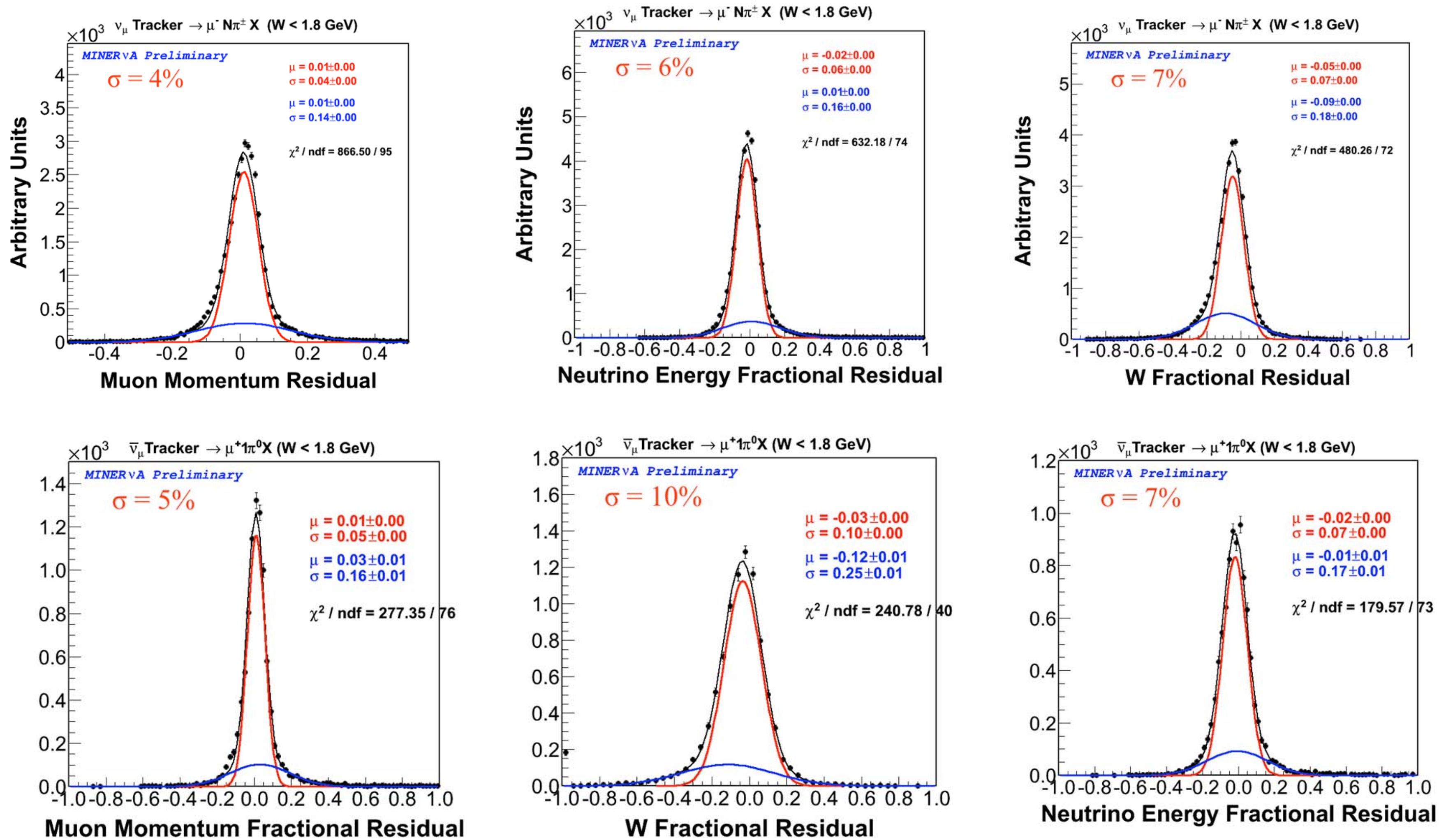
- gcn


ν_μ Tracker $\rightarrow \mu^- N\pi^\pm X$ (W < 1.8 GeV)
MINERvA Preliminary
POT Normalized
3.04e+20 POT
Data
Other
π^0
Interacting Proton
Stopping Proton
Interacting $\pi^\pm$
Stopping $\pi^\pm$
Candidates / 0.02 Score
Pion Range Score


ν_μ Tracker $\rightarrow \mu^- N\pi^\pm X$ (W < 1.8 GeV)
Area Normalized (MC ×0.73)
3.04e+20 POT
Data
Other
π^0
Interacting Proton
Stopping Proton
Interacting $\pi^\pm$
Stopping $\pi^\pm$
Candidates / 5.0 MeV
Michel Energy (MeV)

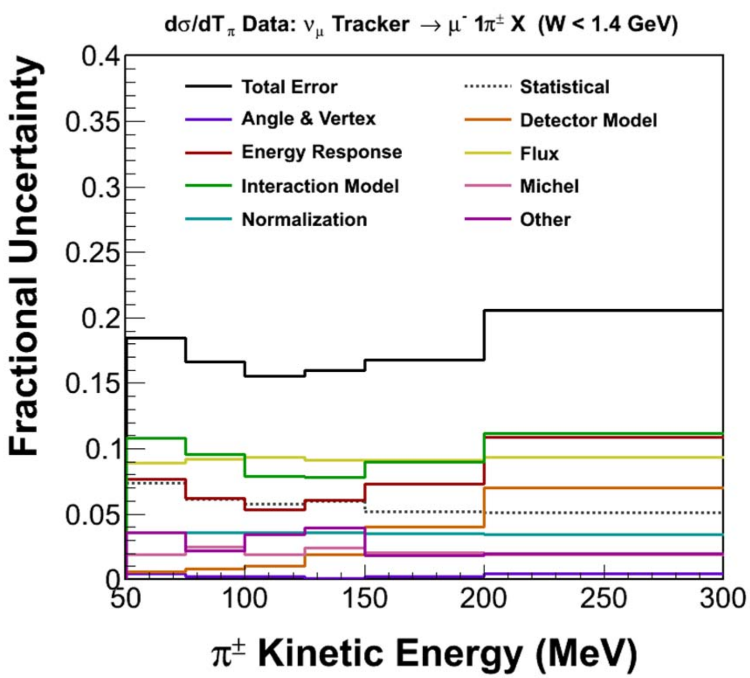

$\bar{\nu}_\mu$ Tracker $\rightarrow \mu^+ 1\pi^0 X$ (W < 1.8 GeV)
MINERvA Preliminary
POT Normalized
1.06e+20 POT
Data
Signal
Background
Fit
Events / (10 MeV/c^2)
$m_{\gamma\gamma}$ (MeV/c^2)

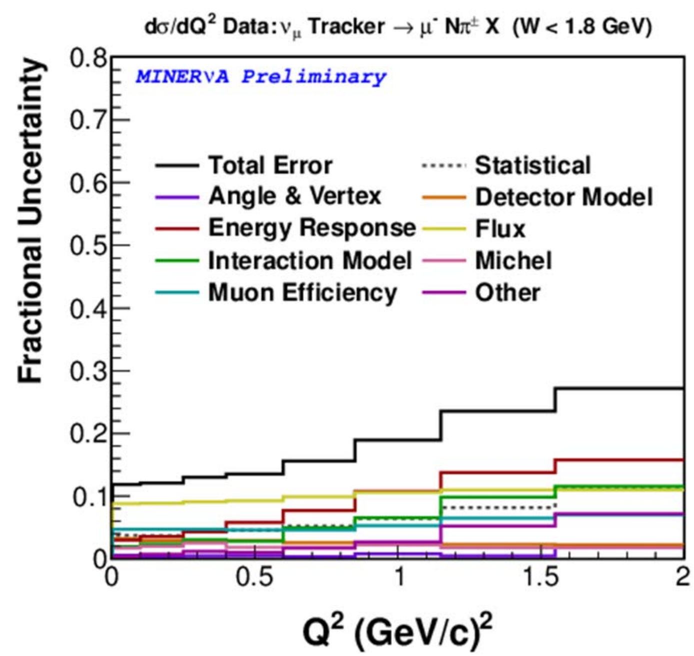
Resolution plots (compared with Monte Carlo)



Systematic errors

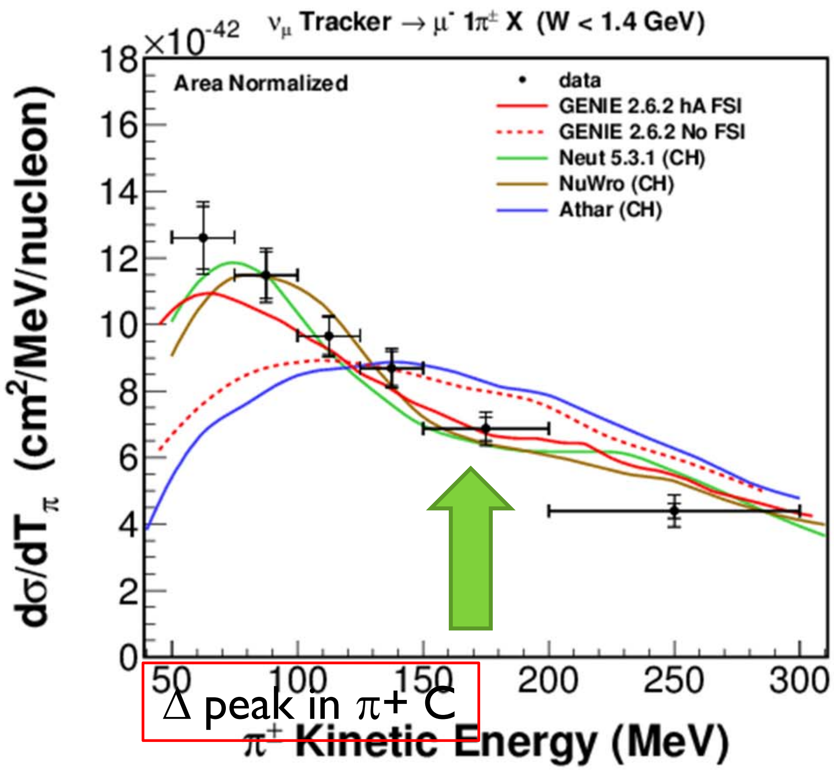
- Move dozens of variables, e.g. MA_{res}, detector energy scale, beam flux fit parameters by $\pm 1\sigma$.

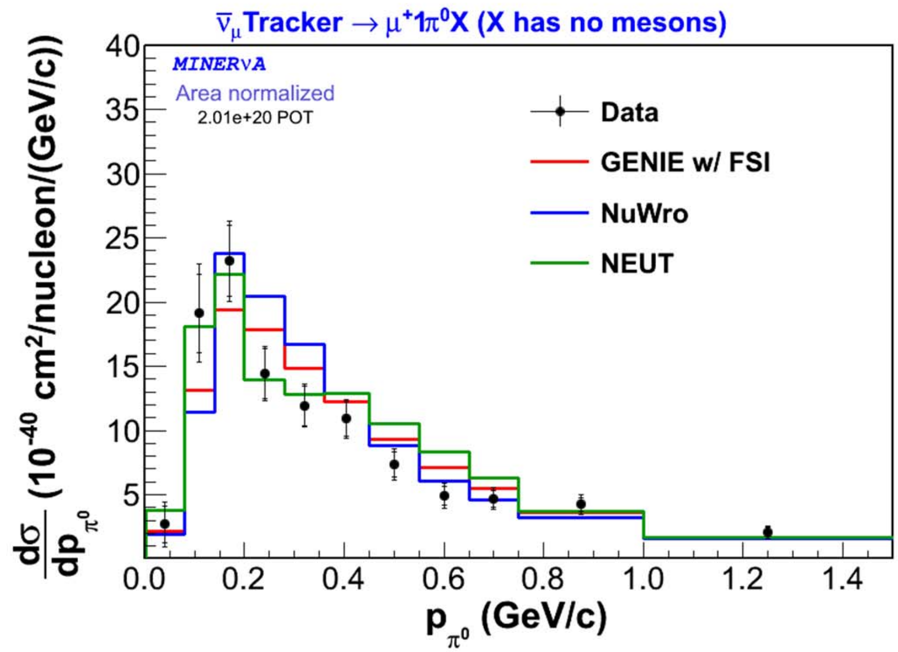




1π results

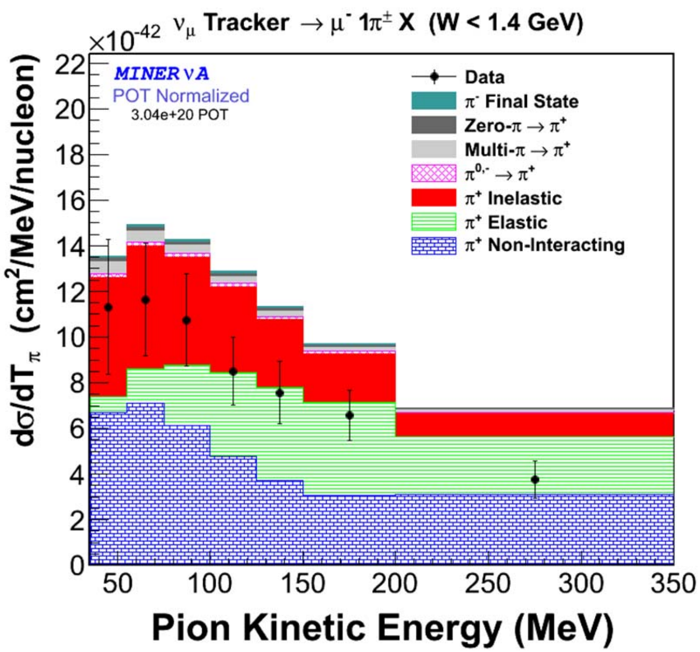
- area normalized (GENIE too high ~30% for π^+)
- Absorption dip is filled in.

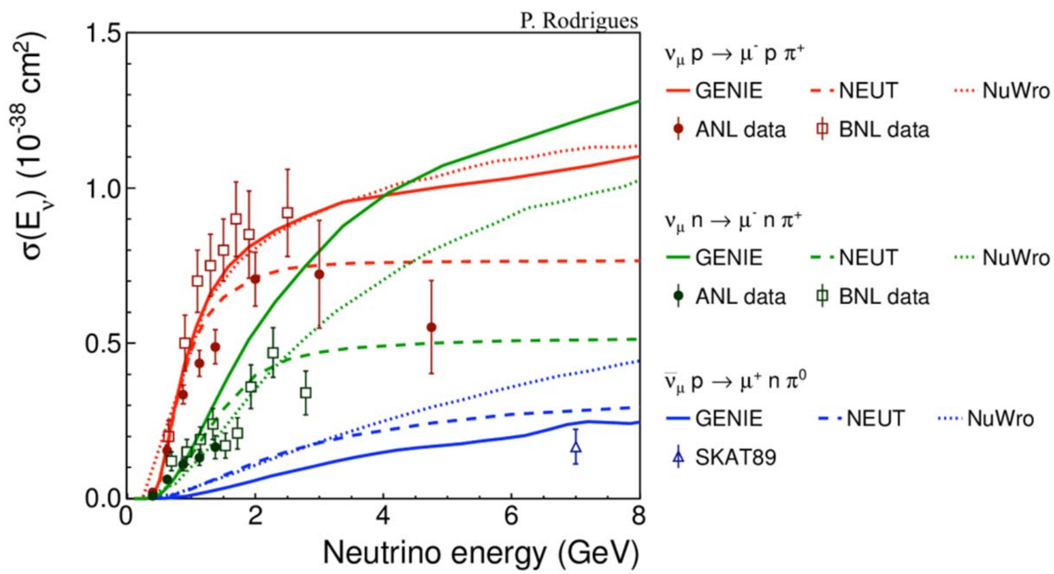




$1\pi^+$ result - detail

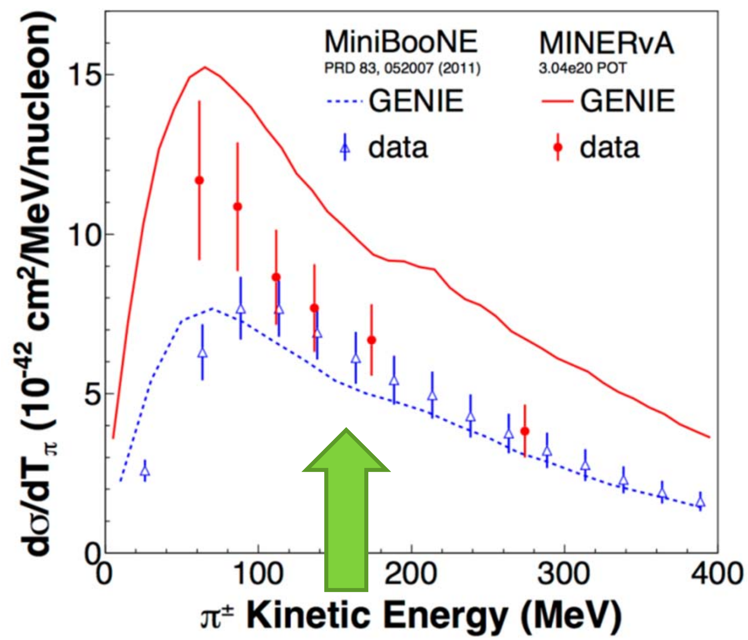
- Shape is very sensitive to FSI details
- Problems with principal vertex evident (old data)





$1\pi^+$ result - detail

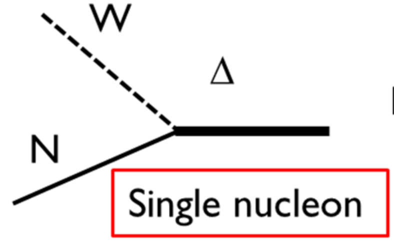
- Wanted resolution of MiniBooNE controversy (why no dip for absorbed pions?)
- Both experiments largely sensitive to Δ formation/decay + π FSI
- Verified lack of a dip, but normalization looks wrong.
- Although MINERvA at higher ν energy, cross section is not much bigger. (new problem)

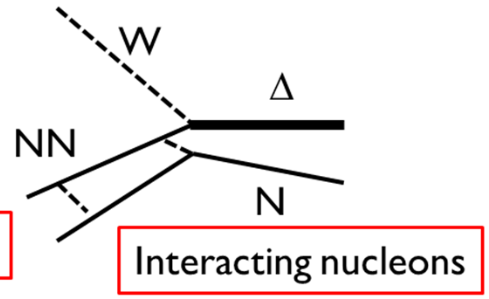


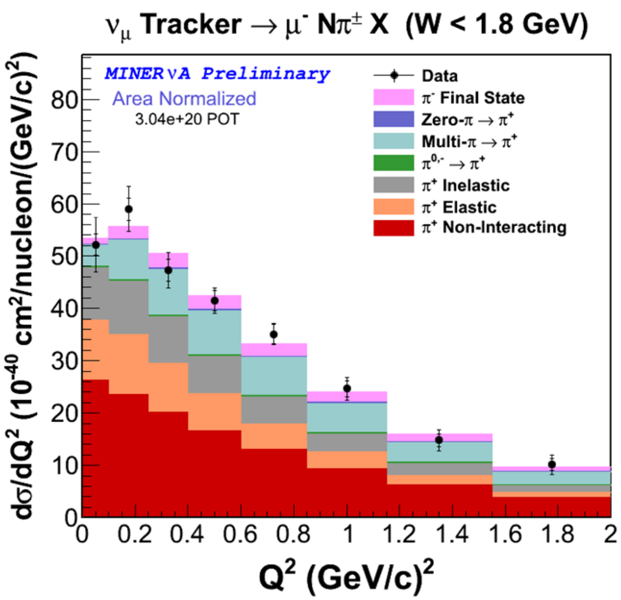
Δ peak in π+ C

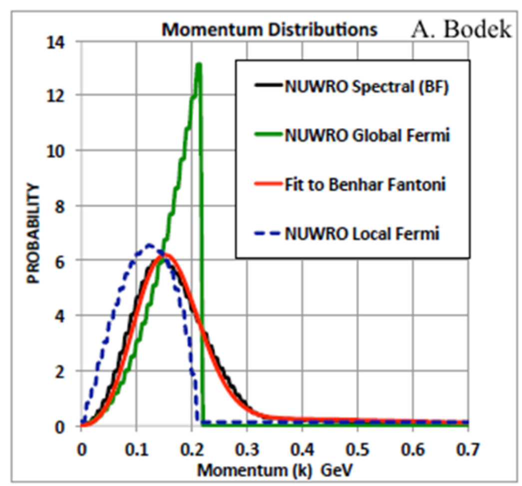
Q^2 tests nuclear structure properties

- Momentum distribution/nuclear medium effects matter.
- FSI doesn't seem to matter for Q^2.
- Nice separation of physics



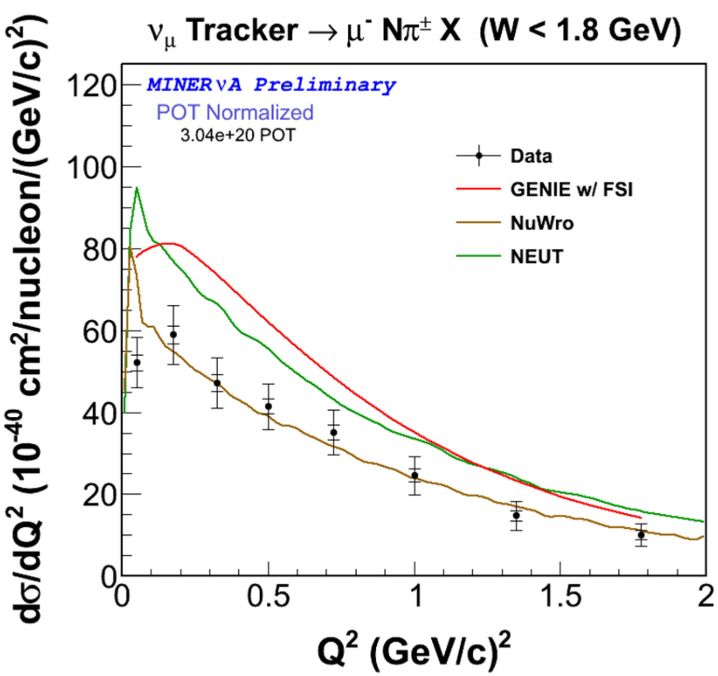


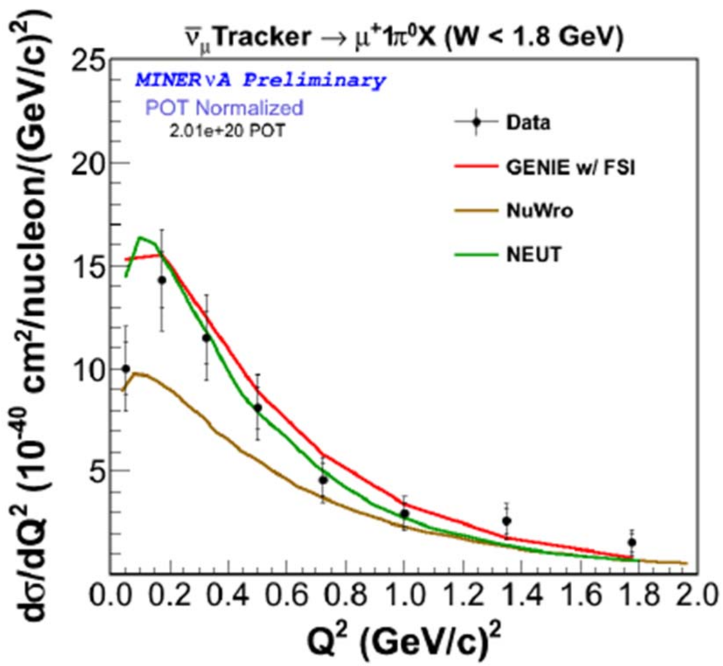




Q^2 results

- All event generators use Relativistic Fermi Gas, no medium effects, no NN correlations.
- Despite simplicity of models, good agreement in shape.
- Charged pion distr has coherent prod, too big in NEUT

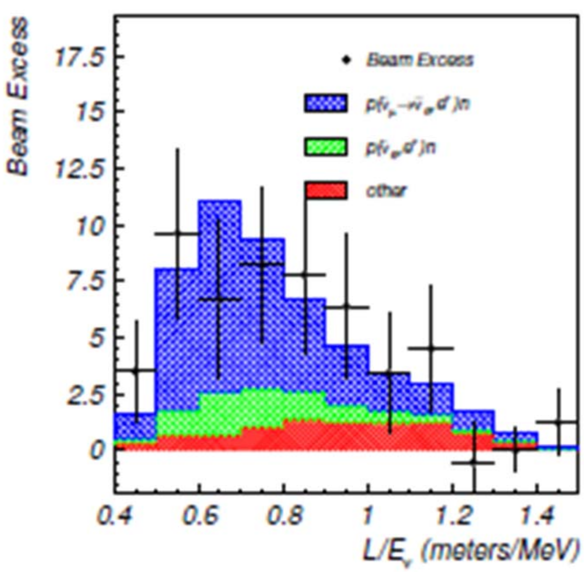




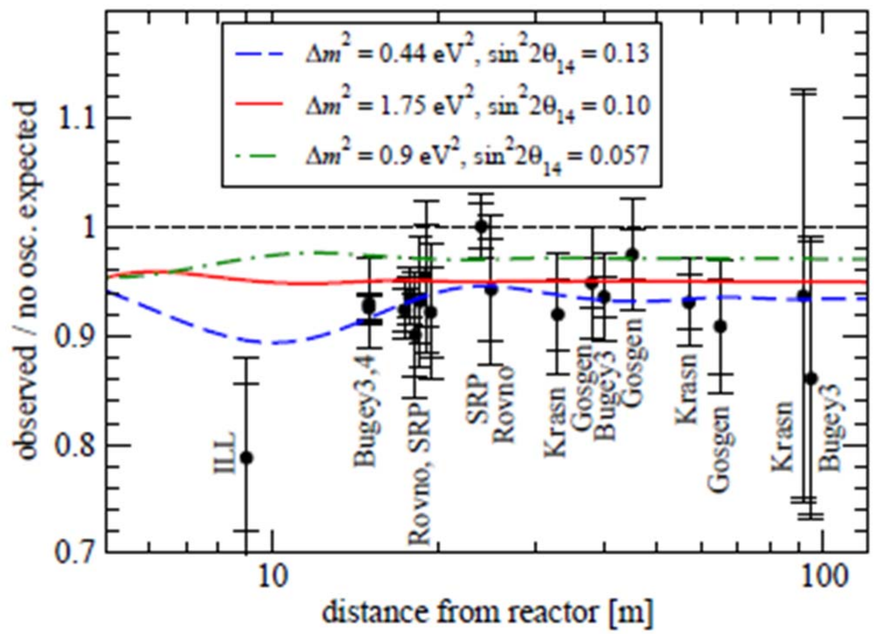
Short Baseline, Reactor experiments

- Testing ground for **new exotic** results, e.g. sterile ν.
- Variety of 2-3σ results, waiting for something definitive.

LSND (PRC, 2001)



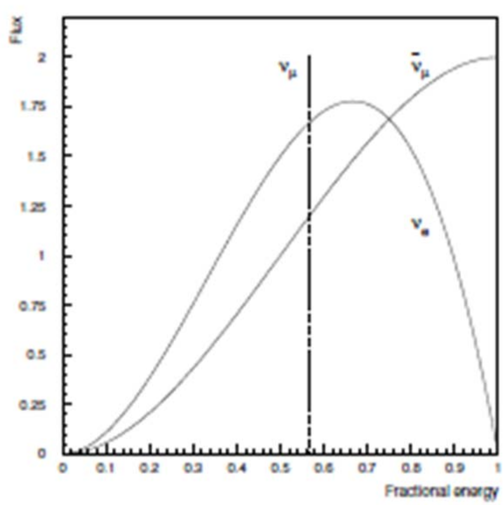
Kopp, Machado, Maltoni, Schwetz
JHEP, 2014

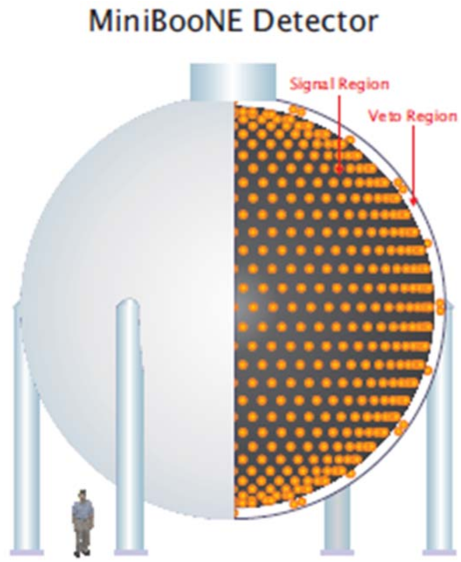


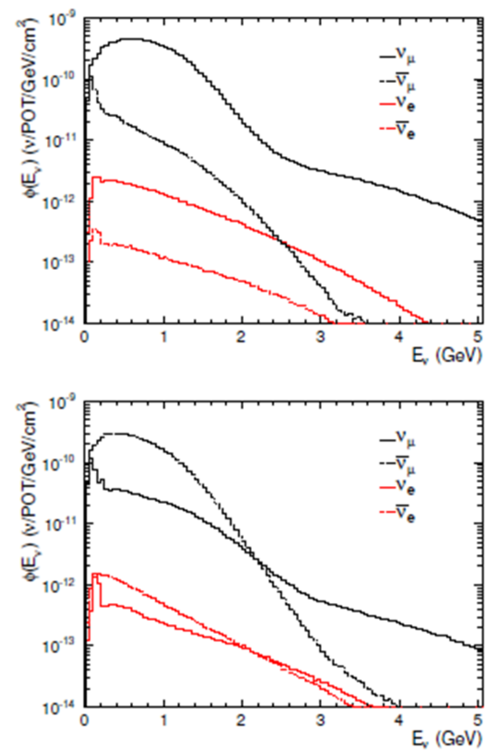
experiments

- LSND was beam dump expt at LANL, π decay at rest is powerful technique (flux known).
- MiniBooNE was accelerator expt at FNAL, large mineral oil Cerenkov detector (CH_2). [no near det]

LSND flux



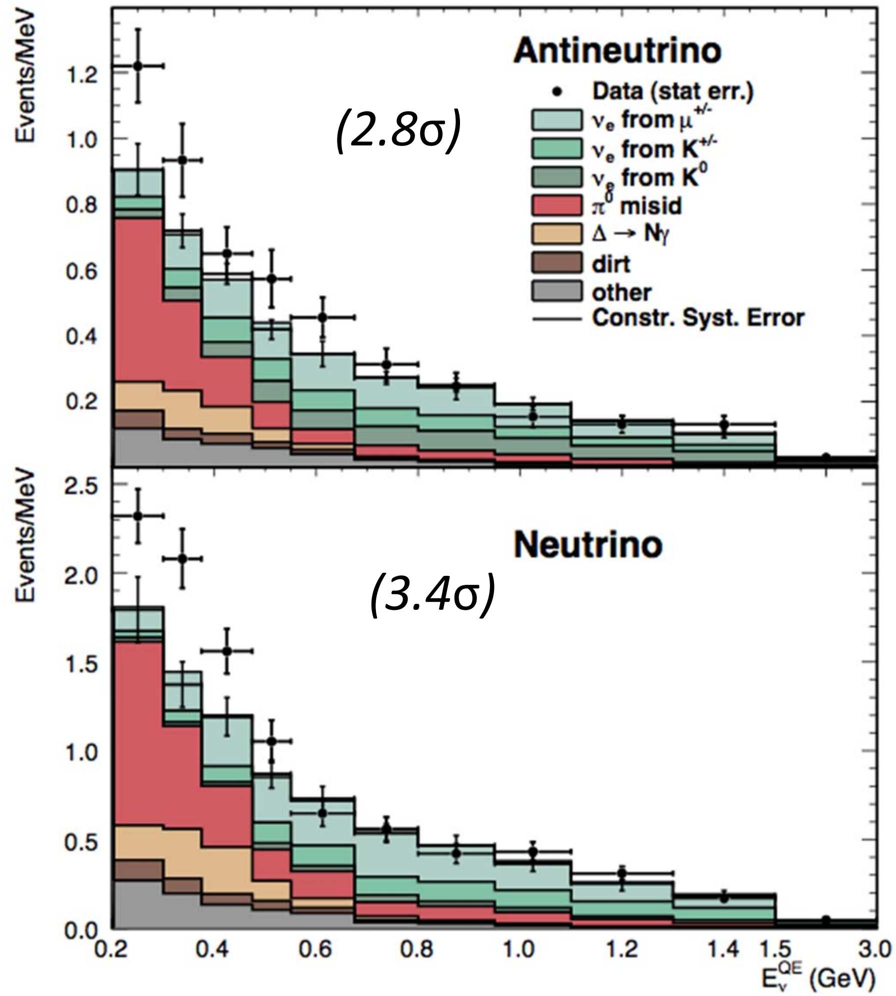




MiniBooNE results

Aguilar-Arevalo et al., Phys. Rev, Lett. 110, 161801 (2013)

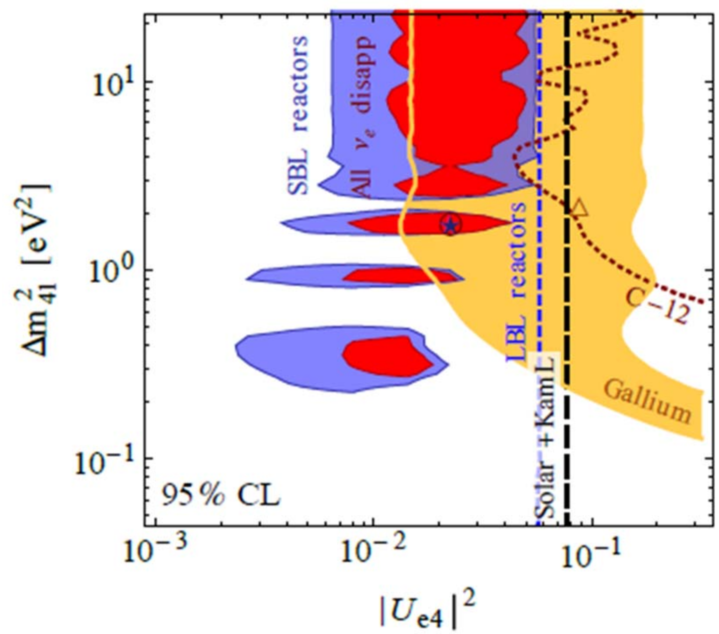
- Goal was to prove or disprove LSND, results mixed.
- Excess at new L/E is surprising.
- Consistency between n and nbar means no CPT violation.



Kopp, Malahorn, Maltoni, Schwetz fitting results

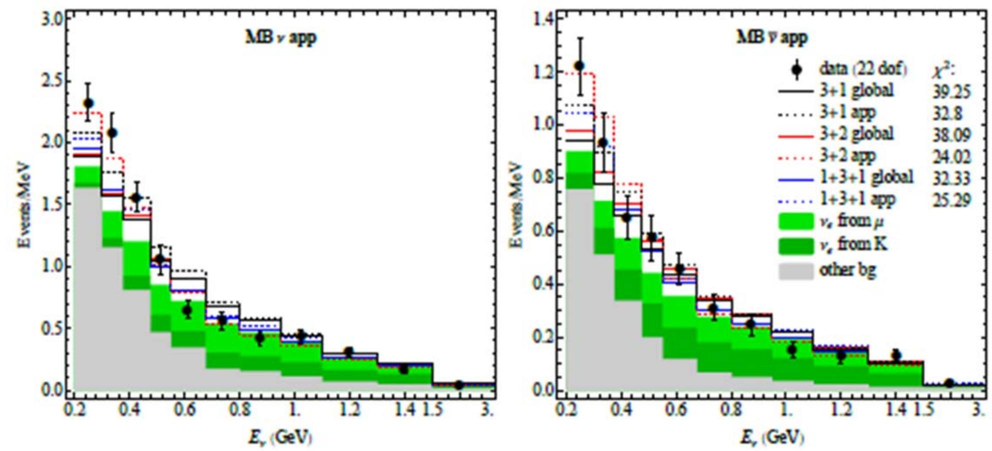
- Define mixing matrix as extension of 3 flavor matrix.
- Consider 3+1, 3+2, and 1+3+1 models (3=valence)
- They consider appearance (LSND, MiniBooNE), disappearance (KARMEN, SciBooNE), reactor experiments.
- Here are sample results for 3+1.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

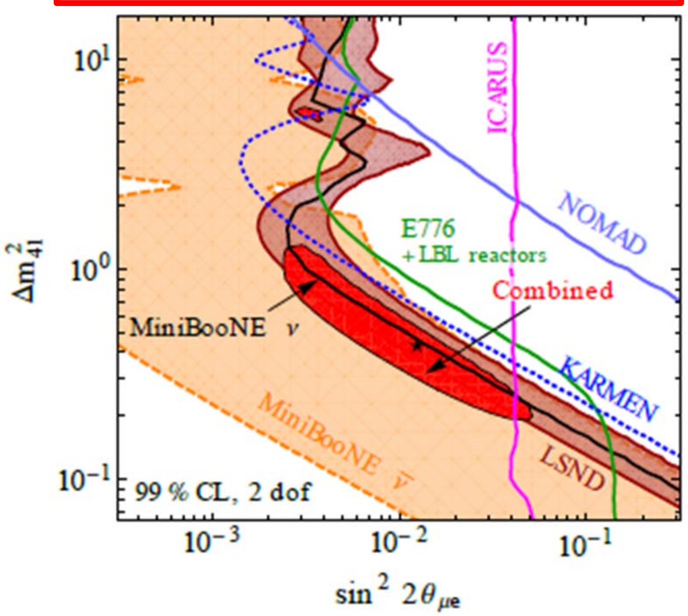


3+1 fit results

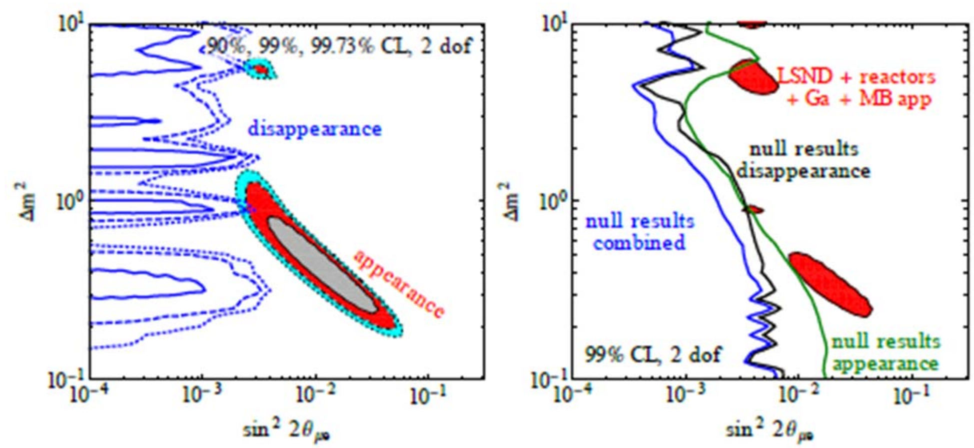
- LSND and MB consistent
- See tension between appearance and global fits
- Total χ^2 suffers



3+1 fit Appearance only



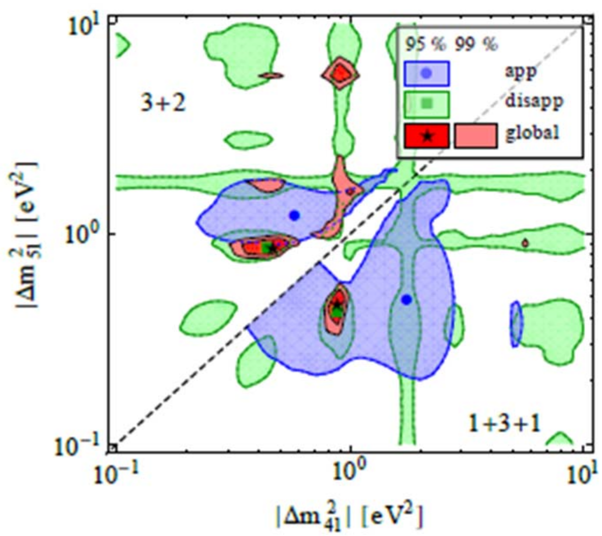
3+1 fit - Appearance +disappearance

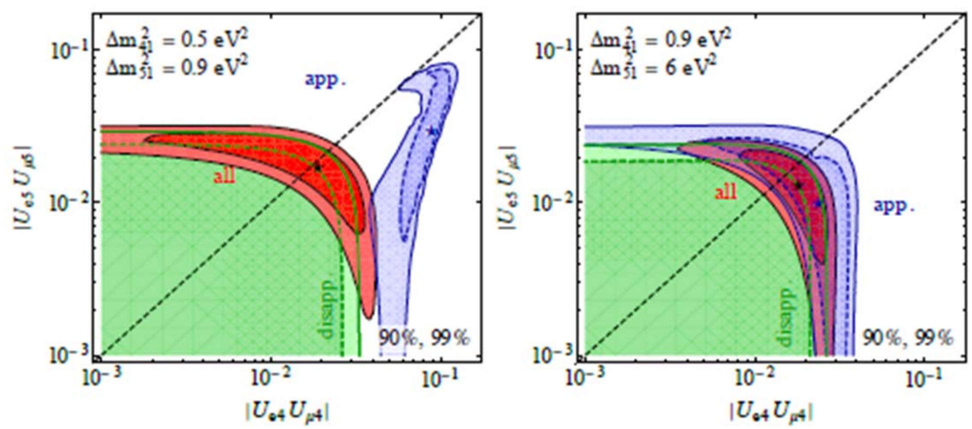


3+2 fit

- Better overall χ^2, but tension between app and disp remains.
- No clean result!

Experiment	χ^2_{3+1}/dof	χ^2_{3+2}/dof	χ^2_{1+3+1}/dof
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/(68 − 2)	72.7/(68 − 5)	74.6/(68 − 5)





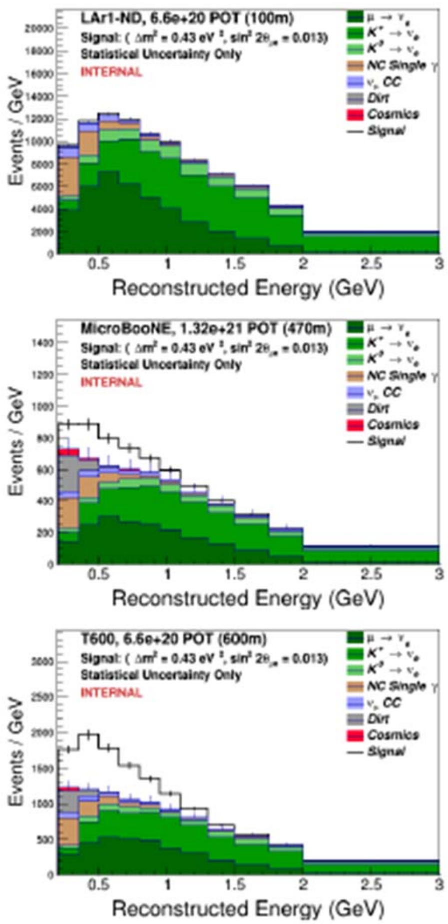
Future - Short base line

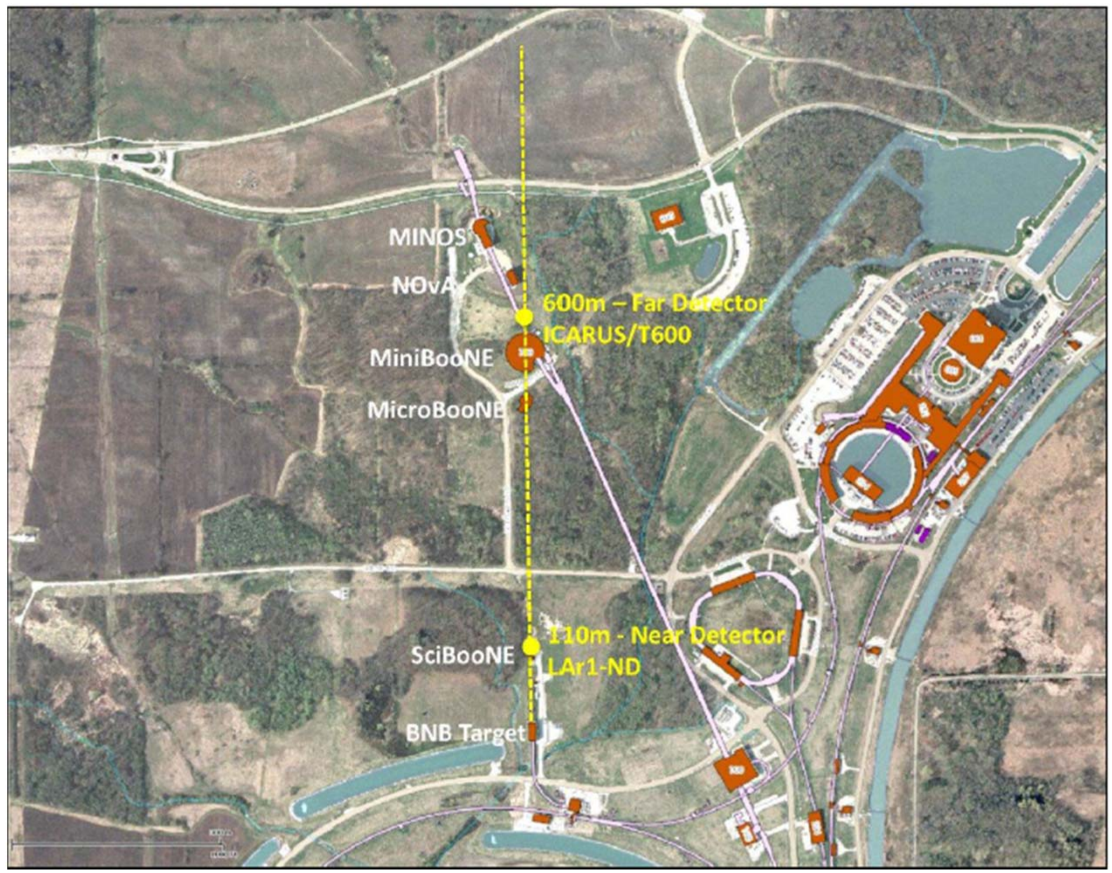
- MicroBoone (170 ton Lar) just finished filling, starts data taking soon. <E_ν>~0.8 GeV. They will separate e from γ vs. MiniB. Focus on sterile neutrinos.
- FNAL will go ahead with building LAr1-ND and moving ICARUS from CERN.
- Intermediate Energy workshop (WINP, http://www.bnl.gov/winp/) had many great ideas – new reactor expts, radioactive source (e.g. ^{51}Cr), new cyclotron idea.
- JUNO (China) 1km base line (approved) . Try to measure neutrino heirarchy

Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t

Plan for BNB experiments

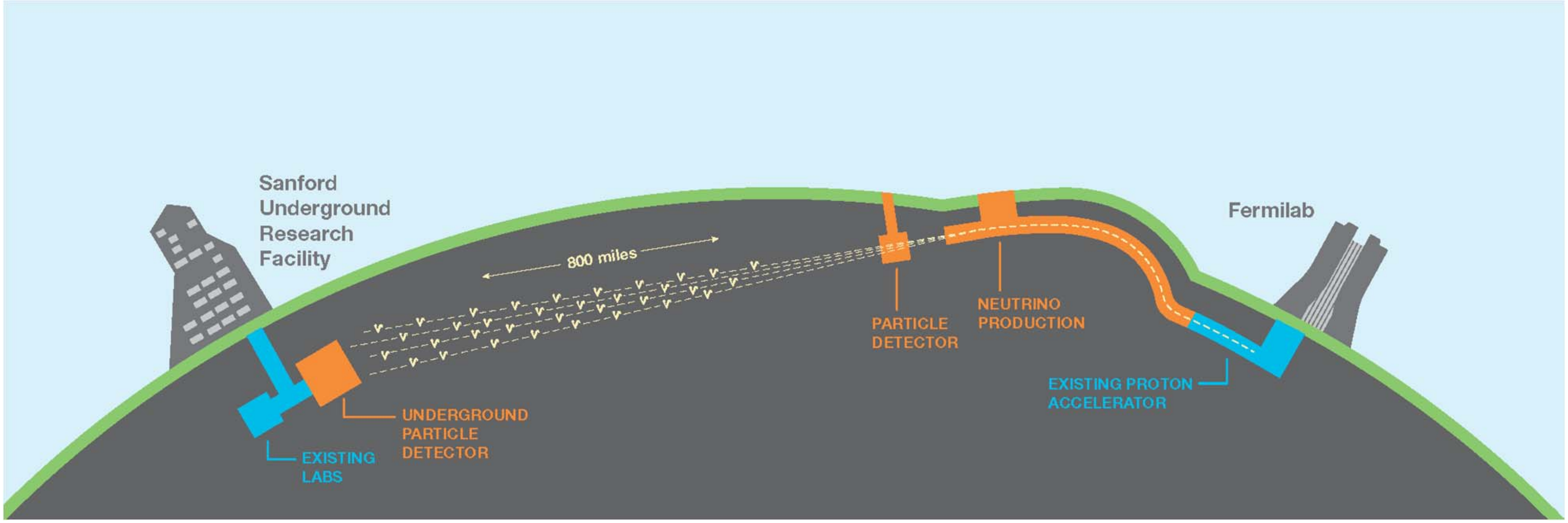
- Finished 2018, plan for 3 years data taking





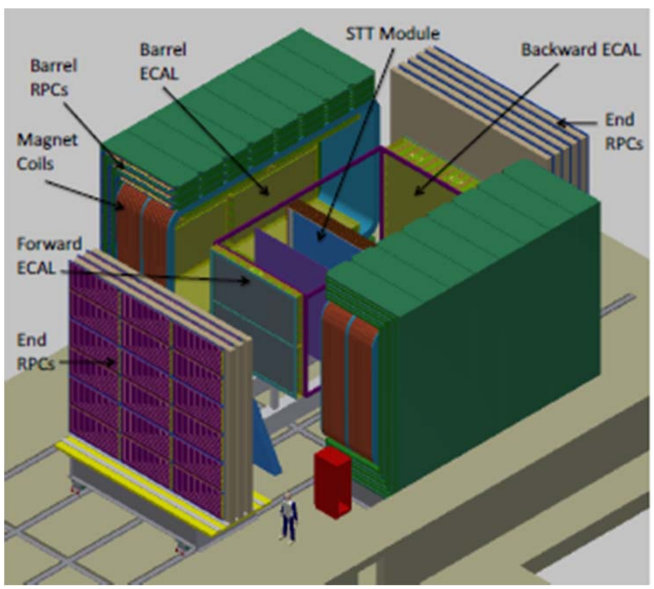
Future - Long base line

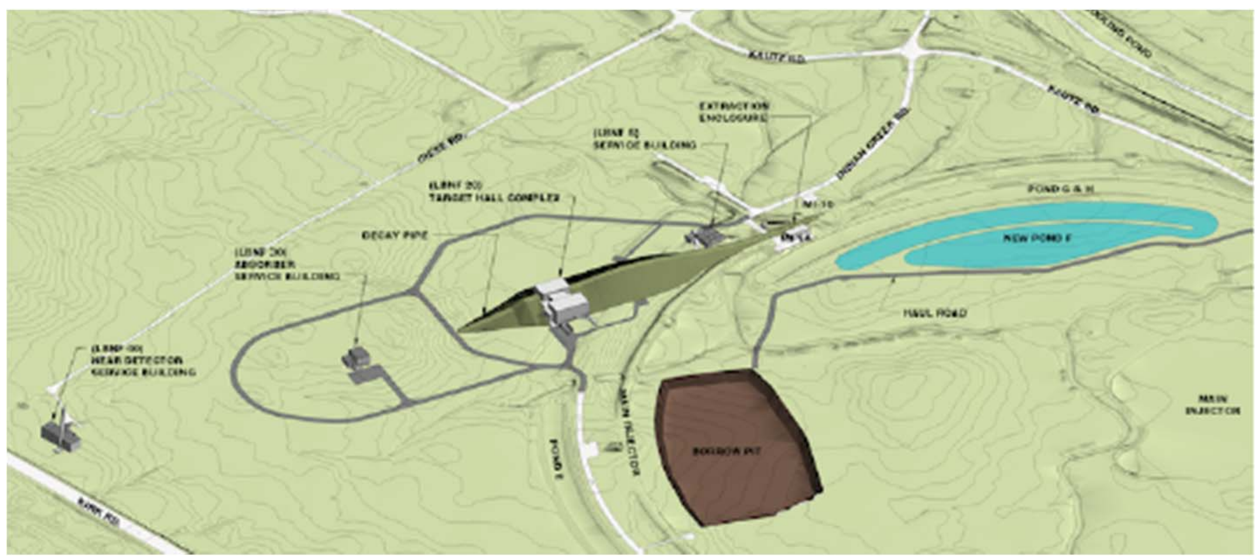
- Deep Underground Neutrino Expt (DUNE)
  - Large international experiment hosted by FNAL
  - 4 x 10kT LAr detector at Sanford Underground Lab (Lead, SD)
  - Mass hierarchy, CP violation
  - Proton decay
  - Supernova neutrinos



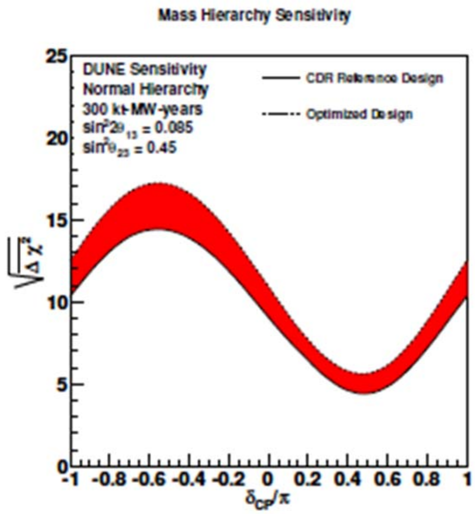
Future - Long base line

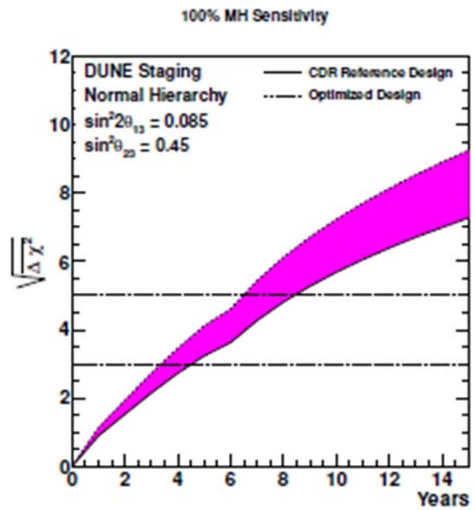
- Deep Underground Neutrino Expt (DUNE) L=1300 km
  - Large international experiment hosted by FNAL (major upgrade)
  - Near detector at FNAL (schematic in left diagram, location in right)
  - 4 x 10kT LAr detector at Sanford Underground Lab (Lead, SD)
  - Mass hierarchy, CP violation with intense (≥1.2 MW) ν, νbar beams
  - Proton decay, Supernova neutrinos





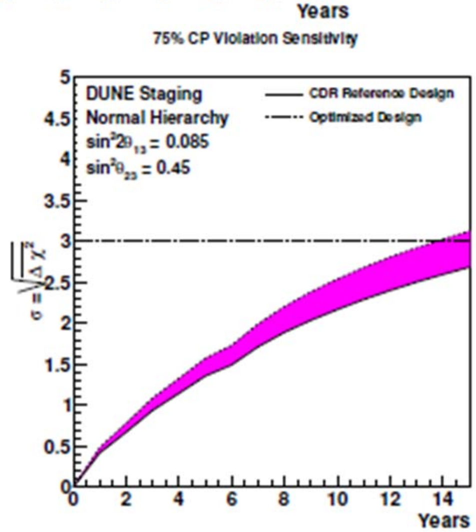
Projected results (CDR)

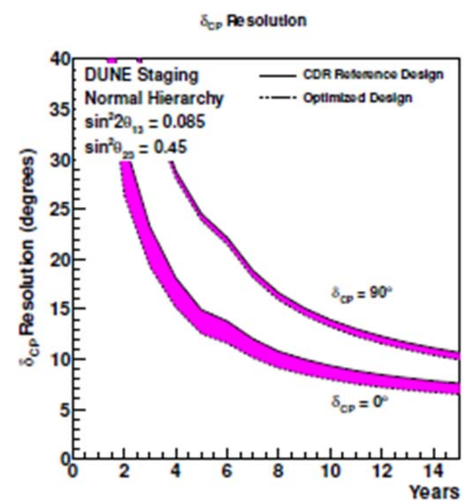




← DUNE error plots (mass hierarchy)

DUNE error plots → (CP viol)



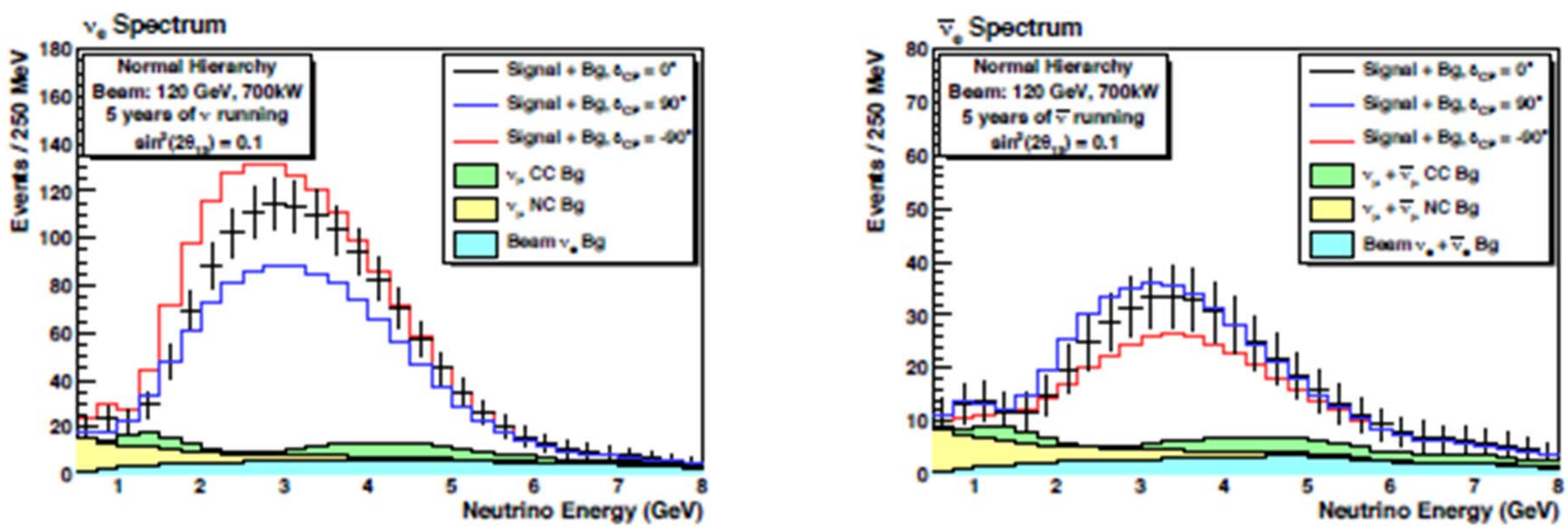


summary

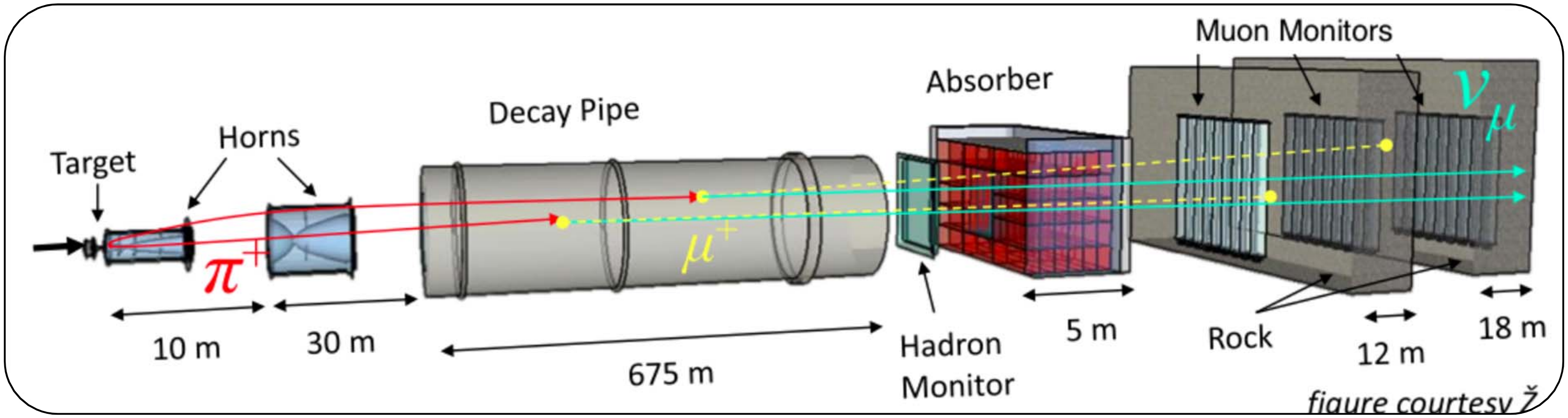
- ν experiments very different than collider
  - Target=detector; favor large, monolithic blocks
  - Beam hard to produce, even harder to monitor
  - Nuclear effects make interpretation tricky
- Recent exciting results
  - T2K sees ν_μ disappearance, $\nu_\mu \rightarrow \nu_e$ appearance (θ_{13}, θ_{13},Δm_{13}^2,)
  - Minerva new pion cross section results don't make things easier
  - Short baseline experiments see surprising results with hints of sterile neutrino
- Future
  - Short baseline experiments at FNAL 1→3 detectors by 2018 (sterile)
  - LBL expts HyperK, DUNE, PINGU proposed for hierarchy, CP

- C

DUNE M
spectra
(2014)

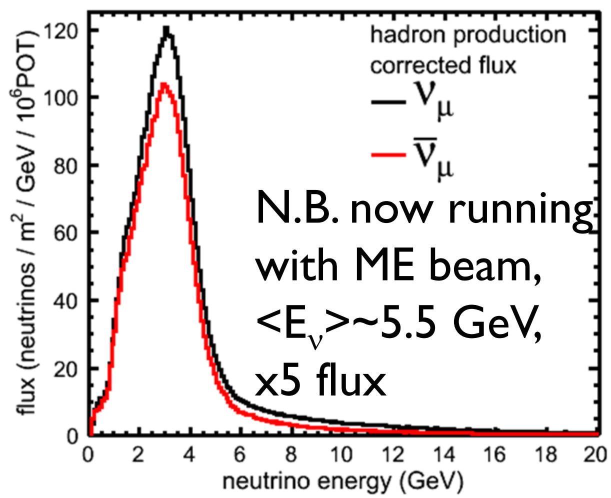


NuMI Beam (~same for MINOS, NOvA)



- NuMI is a "conventional" neutrino beam, neutrinos from focused pions
- For MINERvA, flux must be calculated, use hadron prod data.
- **protons on target (POT) to MINERvA**
  - neutrino (LE): 3.9E20 POT
  - anti-neutrino (LE): 1.0E20 POT

NuMI Low Energy Beam Flux



Experiments are hard, e.g. NuMI at FNAL (MINERvA, MINOS, NOvA)

- Think of neutrons or photons, but worse
  - Need tertiary beam, no tagging, no simple monitoring
  - Need very large, monolithic detector, e.g. 15 kT liquid scintillator

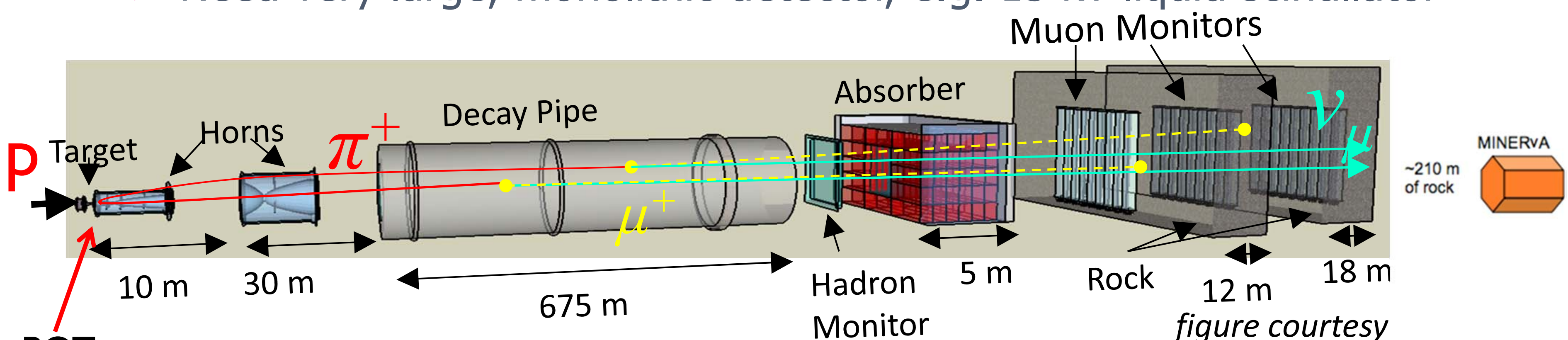
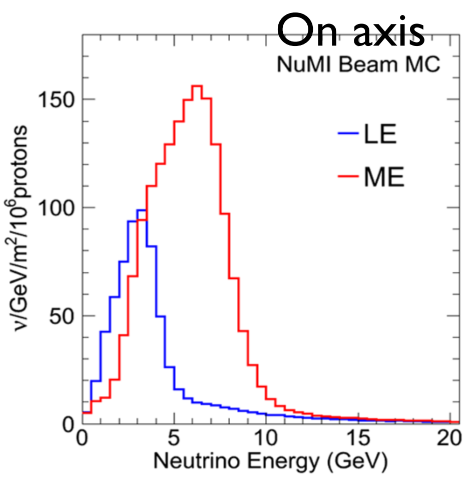
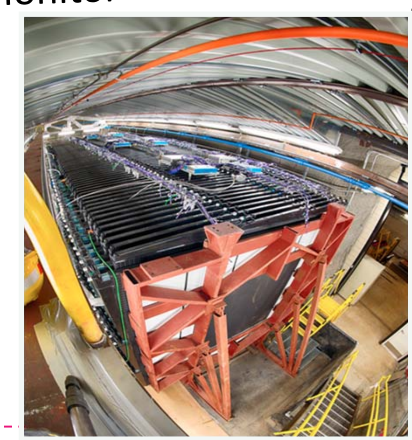


figure courtesy Ž. Pavlović

POT (protons on target)

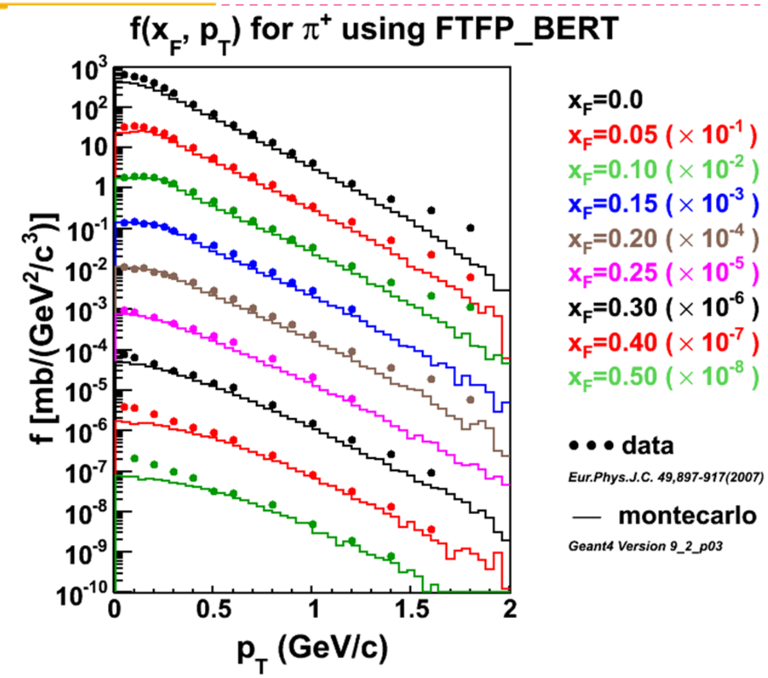


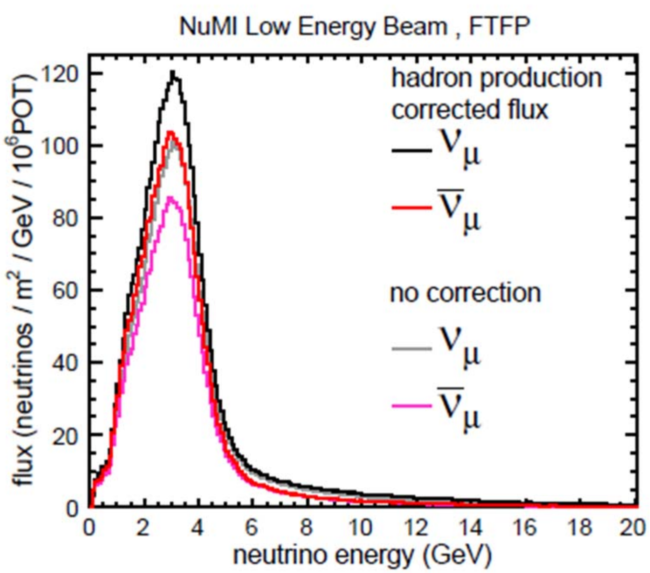


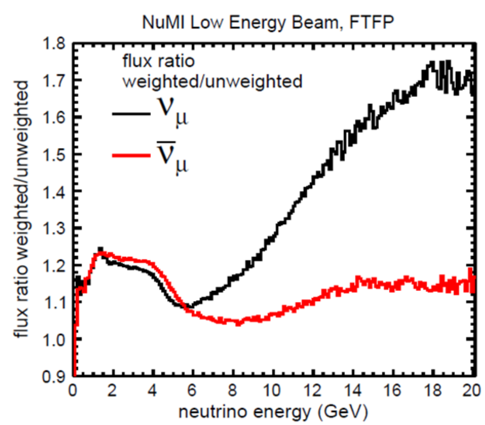
NOvA - liquid scintillator

NuMI Flux Measurement

- Flux measurements are hard!
- MINERvA flux is simulated by GEANT4 and reweighted to match hadron production data from NA49. Recent MIPP publication will help a lot.







Coherent pion production

- Contributes to charged but not to neutral pions here.
- GENIE agrees with MINERvA coherent data, but NEUT large.